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# **A Hardware-in-the-Loop Approach to Independent Wheel Control Development Using a Physical Scale Model as a Low Cost Prototyping Tool**

*Submitted in partial fulfilment of the Engineering Doctorate*

*Executive Summary*

By

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15 June 1999

## **Declaration**

I hereby declare that the work contained herein is the result of original work by the author, except where otherwise stated. All sources of information have been acknowledged by reference. None of the work contained herein has been submitted for any previous degree.

**Paul Faithfull BSc MSc**

## **Acknowledgements**

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## Abstract

Environmental legislation is driving research into new technologies for future automotive products. Electric vehicle technologies have the potential to meet these legislative requirements, but are currently restricted by cost implications. This work focuses on the potential for offsetting this cost against potential benefits of the technology. In particular, the application of a motor at each wheel, facilitating Independent Wheel Control (IWC).

A scale model vehicle is incorporated into a Hardware-in-the-Loop (HIL) simulation for the application of developing IWC strategies. The model uses four motors, each driving a single wheel in order to effect this control. Control strategies are 'rapid prototyped' in MathWorks Simulink™ using an industrial standard tool, dSPACE™, to operate the strategies in real-time HIL simulation.

The application of a control strategy, representative of a conventional 4x4 behaviour, incorporating a lockable centre differential is applied. Shaft compliance is modelled in order to provide a test of the system operation with a transient dynamic response. Stability issues raised through this application are related to signal processing. An estimator is devised in software to overcome these issues, producing a stable system response.

The work concludes that the use of a physical scale model for the development of IWC strategies is inappropriate in the context of supporting the development of a full-scale vehicle due to the complexity of reproducing a scaled tyre. However, in a broader sense, the approach of utilising a physical model has demonstrated significant benefits in promoting the concept of IWC within an industrial organisation, and in assisting product development.

## Nomenclature, Abbreviations, Units and Symbols

### Nomenclature

Hylander project	project to develop the Hylander vehicle.
Hylander vehicle	full scale Hylander prototype vehicle.
Scale model project	project to develop the scale model system to assist in the development of the Hylander project and vehicle.
Scale model system	complete system supporting and incorporating the physical scale model.
Physical scale model	8 <sup>th</sup> scale model representative of the Hylander prototype vehicle.

### Abbreviations

ABS	Anti-Lock Brake System
CAN	Control Area Network
DARPA	Defence Advanced Research Projects Agency
dSPACE	digital Signal Processing and Control Engineering
DTI	Department of Trade and Industry
EC	European Community
ECU	Electronic Control Unit
GUI	Graphical User Interface
IWC	Independent Wheel Control
HE4	Hybrid Electric 4x4 (Rover/DTI project)
HERMES	Hybrid Electric Rover Metro Engineering Study (Rover project)
HERO	Hybrid Electric Realised Off-Road (Rover/DTI project)
HIL	Hardware-in-the-Loop
IPR	Intellectual Property Rights
MoT	Ministry of Transportation
MR	Main Research
PC	Personal Computer
PP	Part Prototypes
R&D	Research and Development
RDI	Research, Development and Implementation
RPP	Rapid Prototyping Process
SAE	Society of Automotive Engineers
TETLEI	Turbine Electric Taxi for Low Environmental Impact (Rover/EU project)
UK	United Kingdom
US	United States (of America)
VMU	Vehicle Management Unit

Units

Mass	Kilogram	kg
Time	Second	s
Current	Ampere	A
Angle	Radian	rad
Force	Newton	N
Power	Watt	W
Electro-motive Force	Volt	V
Frequency	Hertz	Hz
Torque	Newton-metres	Nm
Inertia	Kilograms-metres <sup>2</sup>	kgm <sup>2</sup>
Angular Velocity	Radians/Second	rads <sup>-1</sup>
Electrical Resistance	Ohms	Ω
Density	Kilograms/metres <sup>3</sup>	kgm <sup>-3</sup>

Symbols

$\omega$	Angular velocity	rads <sup>-1</sup>
$\tau$	Torque	Nm

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# 1 Introduction

## 1.1 Background

Environmental legislation has driven the automotive industry to investigate alternatives to the conventional internal combustion engine ever since the early 1970's [1]. This research has resulted in modern vehicles carrying their own exhaust treatment devices, which convert exhaust pollutants through a process of catalytic conversion [2]. As emissions legislation continues to tighten, alternatives are being investigated for the next millennium. In the near term, alternative fuels may prolong the existence of the internal combustion engine. However, billions of dollars are now being invested in electrical based automotive technologies [3], initially to supplement and eventually to supplant combustion based technologies.

Electric vehicle technology has two guises; the pure electric vehicle, where an electrical storage media is used to power a vehicle, or a hybrid, where two or more technologies are combined to overcome their individual drawbacks. A common example of a hybrid system is a 'series' hybrid drivetrain utilising an internal combustion engine driving an electrical generator. An energy storage media, such as batteries, buffer the engine from the power demand at the wheels. This allows the engine to be run at a highly efficient, fixed operating point. Removing transient behaviour from an internal combustion engine also reduces emissions, allowing the stoichiometric operation required for optimal catalyst performance to be maintained [4].

In the Rover Group, an electric and hybrid vehicle department (henceforth referred to as 'the department') was started in 1989. The department performs a role in evaluating the

potential of electric vehicle technology and in the development of a knowledge base to support the application of electric vehicle technologies in future production vehicles. The technology is sourced from a variety of specialist suppliers. The 'value' added by the department is in the integration of technologies into a system, control of the system and in packaging of the system into a vehicle structure. The value to the Rover Group is the potential for the technology to meet future emissions legislation requirements, especially the impending 'Zero Emissions' legislation in the lucrative Californian market [5].

Rover Group currently markets three brands; Rover cars, MG sports cars, and Land Rover off-road 4x4 vehicles. Land Rover products are considerably larger, heavier, and less efficient than the Group's other products (conventional cars), primarily due to the broader operational conditions with which they are designed to cope, and the complex nature of their 4x4 drive drivetrains. As a result, they are the products most liable to fail to meet future emissions legislation using conventional technology.

Land Rover products also lend themselves to the application of electric vehicle technologies. Their physical size provides room to package system components. The brand image is strong, with the products considered to be at the forefront of the off-road vehicle market. As a result, they retail at a higher premium than Rover's on-road products with a greater margin in which to absorb the 'on-cost' of electrical system technology.

For these reasons, the department focused on research into the application of electrical system technologies to support the Land Rover brand. This led to the Turbine Electric Taxi for Low Environmental Impact (TETLEI) project [6], which demonstrated that a

series hybrid drivetrain could improve fuel economy (and hence reduce carbon dioxide emissions) for a 4x4 vehicle. The project also highlighted the cost implications of the technology as the primary barrier to its introduction. As the requirements of emissions legislation must be met in order to compete in a market, they represent no perceivable customer benefit with which to offset this cost.

In 1994, the German automotive manufacturer, BMW, bought out Rover Group. It was recognised within the department that BMW had advanced further than Rover both in the development of electric vehicle technology, and in stronger supplier links. Where work in the Rover Group had been limited to vehicle conversion, BMW had developed a dedicated electric vehicle platform. It became clear that if electric vehicle technology entered a production vehicle, that technology would be supplied through BMW for future Rover products [7]. Thus, BMW would focus on reducing the cost associated with the technology in order for it to become viable in the marketplace.

This provided the department with an opportunity to investigate how the cost of the technology may be offset by benefits for which the customer would be willing to pay a premium. Through this work, the department can support the brand image of Land Rover in the future, keeping the products at the forefront of the market through recognition and protection of potential applications of electric vehicle technology. This change in focus led to a proposal for a completely new form of off-road vehicle drivetrain.

### 1.1.1 The Hylander Project

The Hylander project was proposed in 1995 with the aim; *'To demonstrate step change improvements in off-road performance using the superior drive characteristics of independent electric motor propulsion. The Hylander project goal is to produce the best 4x4 in the world.'* [8]

The Hylander concept is a four-wheel drive vehicle with each wheel driven independently by an electric traction motor. Intended solely for the study of vehicle dynamic performance, the vehicle drivetrain system ignores potential emissions improvements. In order to simplify the power generation system, an engine and generator develop a constant output power sufficient to meet the maximum power requirements of the motors.

The vehicle utilises the concept of Independent Wheel Control (IWC) in order to enhance functionality and performance in both on and off-road driving. The key goals of the system are [8]:

- Maximise off-road ability.
- Minimise terrain damage.
- Simplify off-road driving through repeatability of vehicle behaviour, independent of terrain.

### 1.1.1.1 The Hylander Vehicle

The Hylander vehicle is based on a conventional 4x4-vehicle platform (Land Rover Defender 90). It has 4 motors, each capable of delivering a maximum of 1500Nm of torque at the wheels via a 1:10 ratio gearbox, and 35kW of power. The drivetrain arrangement is illustrated schematically in figure 1.

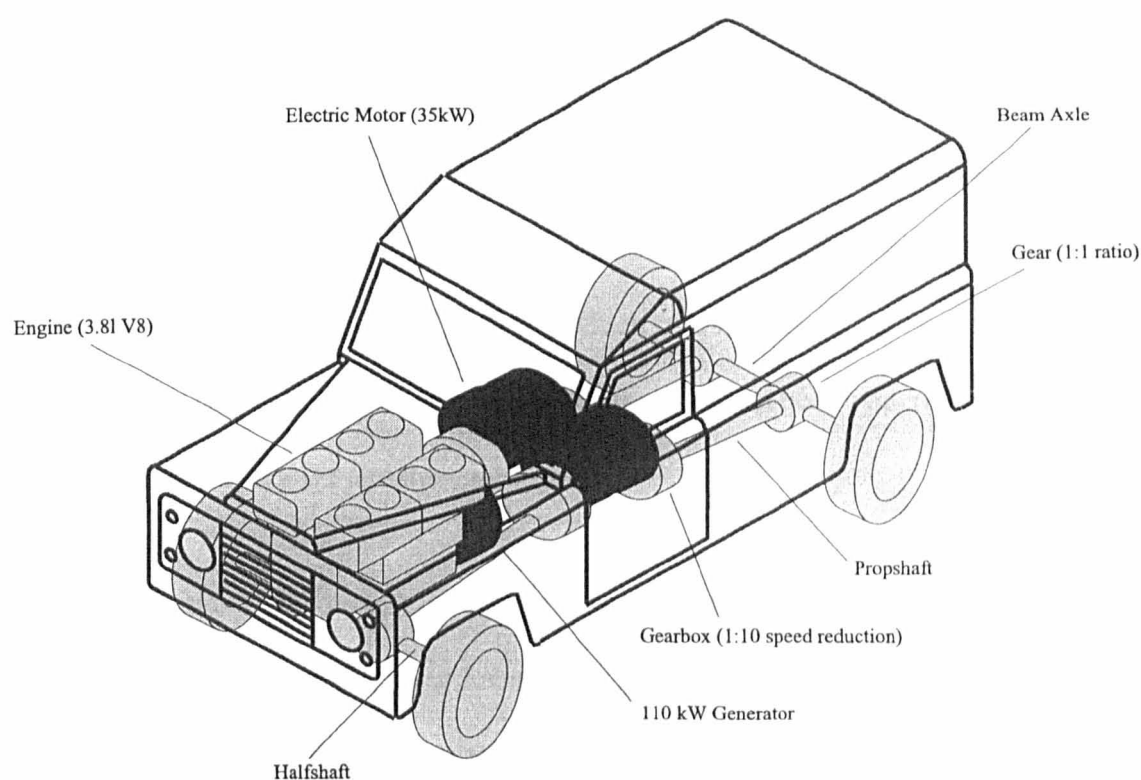


Figure 1. Hylander Vehicle Schematic

### 1.1.1.2 Implications of the Hylander Project on Vehicle Development

In prior work undertaken within the department, predevelopment had been principally through mathematical systems modelling, and computer simulation using the MathWorks Matlab<sup>TM</sup> and Simulink<sup>TM</sup> packages. The simulations were used to specify system components in terms of their energy requirements, and to demonstrate the potential of the technology for improving vehicle emissions/fuel economy. The

knowledge base for this work existed within Rover [9], from suppliers and from published work, for example [10] [11] [12] [13].

The Hylander project predevelopment requires consideration of system component specifications for which off-line simulations are appropriate. Predevelopment also involves the development of IWC strategies to control the dynamic behaviour of the vehicle. This is an area unfamiliar to the department, and in the context of off-road driving, for which little mathematical modelling work has been undertaken, either in industry, nor academia. The interaction between the tyre and off-road terrain is a complex, non-linear relationship, which contains a high degree of random variation due to the non-uniformity of off-road terrain. Much of the research into this area involves empirical measures of terrain [14] [15], and little work has been undertaken to integrate these measures with a vehicle dynamics model.

At the instigation of the project, a rapid evaluation of the potential of IWC was required. Similar projects were progressing for military purposes, most notably in the US where the US Defence Advanced Research Projects Agency (DARPA) had converted a military HUMMER vehicle to IWC [16]. The potential for such projects to generate Intellectual Property Rights (IPR), e.g. patents, which may hinder Land Rover's product development in the future was a concern.

The development of mathematical models which describe the dynamic behaviour of the Hylander vehicle on a variety of off-road terrains would be difficult and potentially unrealistic due to lack of experience in the department in this field of modelling, and the complexity of the tyre/terrain interaction. Hence other tools were deemed to be required for the development of IWC, prior to the completion of the Hylander vehicle.

## **1.2 Aims of the Portfolio**

The aims of the portfolio are:

- To develop a tool for the rapid prototyping of IWC strategies in the context of the Hylander project.
- To validate that this tool is 'fit for purpose' through its application in the development of an IWC strategy.
- To support the Hylander vehicle project through this application.
- To support the future development of the Land Rover brand and business.



### 1.3 Main Themes Of The Portfolio

The main themes developed through the portfolio are:

**Physical Scale Modelling** - one component of the system used to evaluate IWC strategies in this work is an 8<sup>th</sup> scale physical model, representative of the Hylander vehicle [17].

**Rapid Control Prototyping** - a control algorithm developed in a high level language (Simulink<sup>TM</sup>) is automatically coded to a hardware microcontroller platform (dSPACE<sup>TM</sup>), facilitating real-time control of a physical plant. The system provides on-line parameter tuning and data logging via a host Personal Computer(PC) [18] [19] [20].

**Hardware in the Loop (HIL) Simulation** - the running of a computer based simulation with a component of the simulated system realised in physical hardware. This hardware component will commonly be a system element, which does not lend itself to mathematical modelling. Thus the HIL can provide a rapid solution by removing the lengthy process of developing a theoretical mathematical model of a complex system component [21] [22].

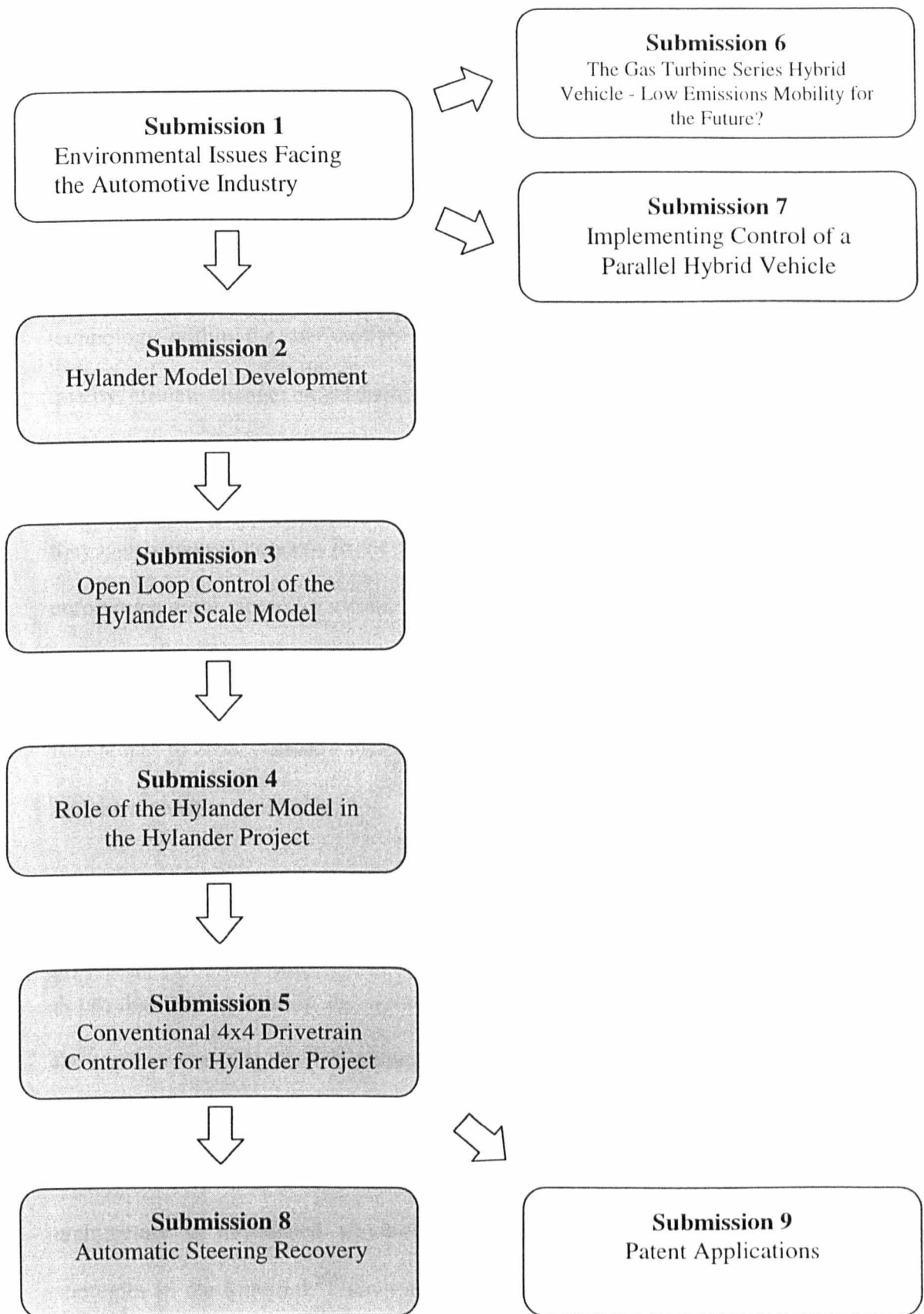
**Independent Wheel Control (IWC)** - Each wheel is controlled as an independent system, as well as a part of the whole vehicle system [23][24][25]. In the context of this work, this concept relates to total independence of wheel operation. In this manner the concept differs from current wheel control developments which utilise engine and braking control, for example the Bosch VDC system [2].

## **1.4 Structure of the Portfolio**

The main body of the portfolio is broken down into nine separate reports, henceforth referred to as submissions. Two further submissions exist in the portfolio, a personal profile, which is incorporated for the requirements of the Engineering Doctorate, and the Executive Summary, which provides an overview of the submissions, and how they interrelate. The author's suggested order of reading is illustrated graphically in figure 2 (from top to bottom). Core submissions relevant to the aims of the project are highlighted through shading.

Submission 1 provides a general background to the early drivers behind the research into new vehicle drivetrain technologies. Two published papers (submissions numbered 6 and 7) are more general reference documents illustrating the author's contribution to the development of technology within the department, outside of the main project, and to the academic body of knowledge.

Submission 9 is a collection of six patent applications which have been entered into the Rover IPR protection system, but at the time of writing have yet to be filed. They represent both the generation of IPR through the Hylander scale model project, and illustrate thinking beyond the scope of the current Hylander vehicle. As their right to claim invention has not been validated, they are included as an Appendix to the main body of the portfolio for reference purposes only. Submission 8 also describes a patent application. This application is differentiated from the applications in submission 9 as it has been published in the UK, EU and US, demonstrating its claim of invention.

*Figure 2. Suggested Order of Reading Submissions*

## **1.5 Overview of Submissions**

### **1.5.1 Submission 1 - Environmental Issues Facing the Automotive Industry**

A background investigation into the principal external drivers behind research into new technology within the automotive industry is provided. The issues covered are air quality, climate change, recyclability and noise.

It concludes that whether these issues present real environmental hazards is arbitrary as they cause enough concern in the public and government to drive legislative measures enforcing a requirement for cleaner, quieter, and more eco-friendly automobiles to be on the market in the coming years.

References to other portfolio submissions made in this document have been superseded, and are no longer applicable.

### **1.5.2 Submission 2 - Hylander Model Development**

A physical scale model of the Hylander vehicle is identified as an appropriate tool for the rapid prototyping of IWC strategies. Modelling theory is explored in relation to the requirements of reproducing vehicle dynamics both on and off road. An appropriate scale is chosen and justified based on the constraints of the project. A system architecture is introduced which facilitates the rapid prototyping of IWC control strategies in the Simulink<sup>TM</sup> environment. These control strategies can then be run in real-time using dSPACE<sup>TM</sup>, a hardware/software combination dedicated to control system prototyping for real-world application.

A scale model structure and a software framework providing signal processing is prototyped, and further developed in submission 3.

### **1.5.3 Submission 3 - Open Loop Control of the Hylander Model**

The Hylander scale model system is developed such that open loop control is possible, with instrumentation in place for the application of a closed loop controller. The control approach proposed for the vehicle is a specified torque output at the wheel.

A dedicated current feedback motor controller controls the torque output of the motor. The wheel torque is described as a function of the motor current and wheel speed by a mathematical characterisation of the drivetrain, validated by experimental testing. Instrumentation requirements for IWC strategy implementation are specified and the required instrumentation and signal processing are integrated into the system. The physical build of the model is completed, meeting a high proportion of the requirements of being representative of the full scale Hylander vehicle.

The system is validated as operating in the intended manner with a simple open loop controller. Further validation against the Hylander vehicle for a true measure of representative dynamic behaviour is an identified requirement. The proposed scope of use is limited to concept generation and testing, and control strategy research.

#### **1.5.4 Submission 4 - Role of the Hylander Model in the Hylander Project**

The role of the scale model project in the full Hylander project is highlighted, and how that role is fulfilled is described. A formal processes for development of IWC strategies using the scale model system is introduced to support the Hylander project.

The author developed a framework that is introduced to assist in the planning and control of IWC strategy development, based on ideas generated by the 'customer'. The customer is limited by external constraints to the Hylander development team [26]. The role of the scale model system in the full-scale vehicle Research, Development and Implementation (RDI) process is highlighted.

A process for rapid prototyping IWC strategies is proposed based on current literature. Knowledge transfer from the development of the scale model system to the full-scale vehicle is highlighted, illustrating benefits of producing a representative physical scale model.

#### **1.5.5 Submission 5 - Conventional 4x4 Drivetrain Controller for Hylander Project**

The use of the scale model system in supporting the Hylander project at a conceptual level is demonstrated through the development of a complex, closed loop control application. Through this demonstration, a case study of the IWC prototyping process is provided, and the limits of the system tested.

The chosen application is taken from the planning framework introduced in submission 4, and controls the physical scale model such that it represents the dynamic behaviour and operational modes of a conventional 4x4 vehicle. The terrain chosen for this application is flat, uniform terrain, representative of tarmac.

A mathematical model of a 4x4 drivetrain and vehicle are developed capable of representing linear motion on a hard, uniform surface. The inclusion of transient dynamic behaviour in the drivetrain model provides a test of the capabilities of the HIL simulation technique.

The drivetrain and vehicle models are validated through off-line, computer-based simulation against current literature. The drivetrain model is used in a real-time HIL simulation, replacing the simulated vehicle model with the physical scale model. Stability problems not encountered in the off line simulation, and the potential for them to occur on the full-scale vehicle are highlighted. From lessons learnt, the vehicle simulation model is refined. A software solution to the stability problems is developed and validated for a number of operational conditions using HIL simulation.

#### **1.5.6 Submission 6 - The Gas Turbine Series Hybrid Vehicle - Low Emissions**

##### **Mobility for the Future?**

The work described in this submission assists in the predevelopment of a series hybrid vehicle project, TETLEI, through the development of a reverse dynamic simulation based on vehicle drive cycles. A model of the vehicle drivetrain is produced and simulated using the Matlab<sup>TM</sup> simulation language. The simulation provides information on energy requirements in the system.

A joint paper describing the work was co-authored and presented with Dr. A. Davis at the Institute of Mechanical Engineering Autotech Conference, 1995.

#### **1.5.7 Submission 7 - Implementing Control of a Parallel Hybrid Vehicle**

A control system design for both hardware and software for a parallel hybrid vehicle project, (Hybrid Electric Rover Metro Engineering Study, HERMES) is developed. The author's input is limited to the development of operational moding, and the generation of maps to control the vehicle subsystems. The author also proposed a structure for the vehicle management unit (VMU). The project failed to reach implementation.

A joint paper describing the work co-authored with C. Bourne and C. Quigley was published in the International Journal of Vehicle Design, Volume 17, No. 5/6 (Special Issue), 1996.

#### **1.5.8 Submission 8 - Automatic Steering Recovery**

The work described in this submission aims to improve on and off road ability of a vehicle through the application of IWC to increase front wheel torque when braking and steering. The idea has been filed for a patent in the UK, EC and US.

The patent is co-authored with C. Bourne of the Rover Group. The author contributed by providing the supporting theory for the idea, and provided a broader perspective to its application.



### **1.5.9 Submission 9 – Patent Applications**

This submission comprises a collection of patent applications relating to the Hylander project, including both current and potential future developments. The patent applications are listed below, grouped according to the area of technology they address:

#### **IWC Strategies**

- Steer by Torque Differential
- High Mue Turn on Spot
- Off road Trak-tion
- Tyre Tread Cleaning

#### **Instrumentation**

- Accelerometer Vehicle Tracking
- Speed Measurement Lag Compensation and Rotational Resistance Estimation

The patent applications relating to IWC strategies are all co-authored with M. Ranson of the Rover Group. The patent applications relating to instrumentation are the sole work of the author.

### 1.6 Structure of the Executive Summary

This executive summary provides an overview of the work undertaken within the portfolio. In figure 3, its structure is illustrated schematically, showing how the focus of the work is funnelled from a broad, global perspective to a specific application within the Hylander scale model project, and then expanded to consider the wider potential of the work.

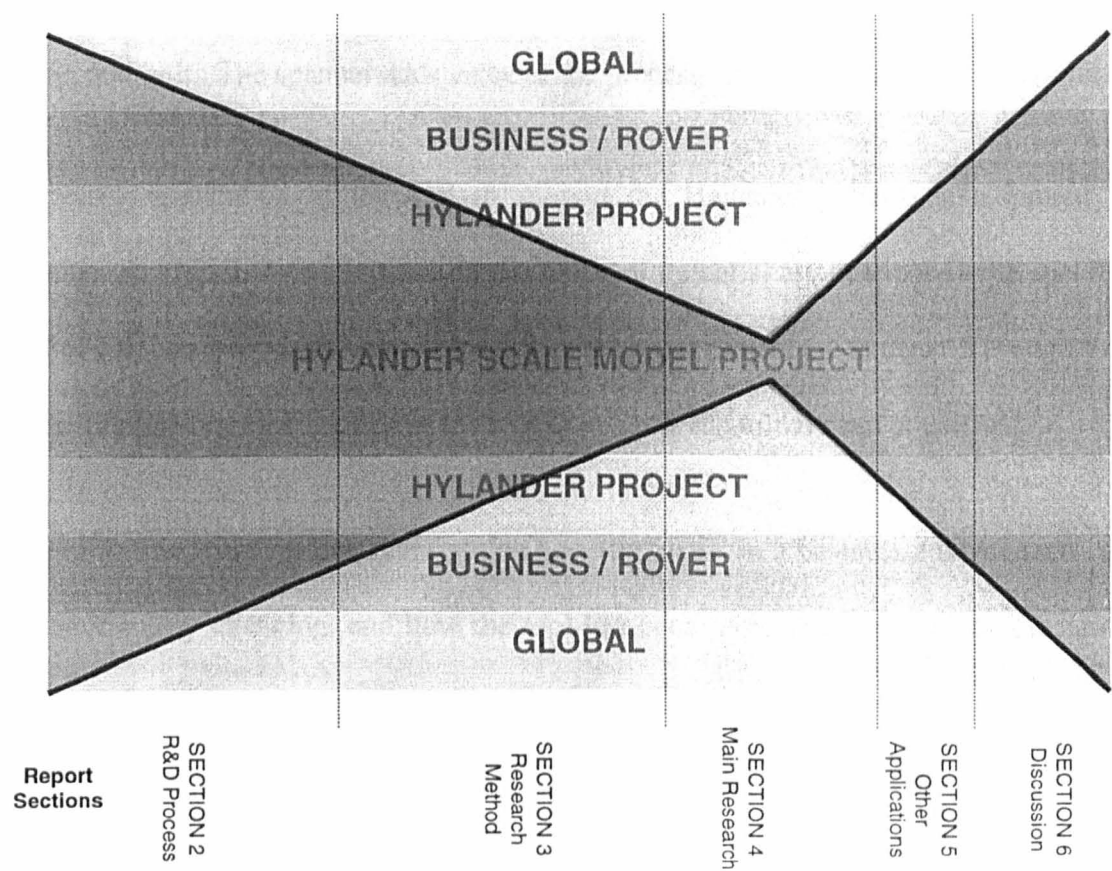


Figure 3. Executive Summary Structure

Section 2 of this report starts with a broad view, identifying generic criteria that highlight the requirement for an approach or tool to improve the research and development process, both in a global context, and more specifically to the business environment (Rover Group). Using these criteria, the requirement for a tool in a

specific context (Hylander project) is identified and an appropriate tool developed in section 3.

The research and development process exists to meet an initial business or technical need or problem. The tool improves the process of meeting this need, but does not meet the need in itself. The need is met through the specific application of the tool. For example, a spanner does not hold an aircraft together, the nuts and bolts do. The requirement of a spanner is to tighten the nuts and bolts, improving the joining made by the nut and bolt. The spanner adds value to the process, but not in itself to the product.

A specific application of the tool to support the Hylander project development is described in section 4. This is one of a number of potential applications in the specific field of IWC development, chosen by the scale model project customers. Through this application, the appropriateness of the tool to meeting the initial need is verified.

The work then broadens out, highlighting how the 'need' in a business environment can be continuously changing, and how the tool has been applied to support the changing needs of the Hylander project and the business. This demonstrates that the potential applications of the tool or technique are not limited to the specific application of IWC strategy development.

To conclude the report, the potential of the tool or approach is discussed in a broader, global or generic context, closing the loop on the initial generic requirement identification.

## **2 Research and Development (R&D) Process**

### **2.1 Definitions**

From [27], R&D in an industrial context are defined as;

Research – ‘the process used by an organisation to acquire new scientific or technical information and knowledge’.

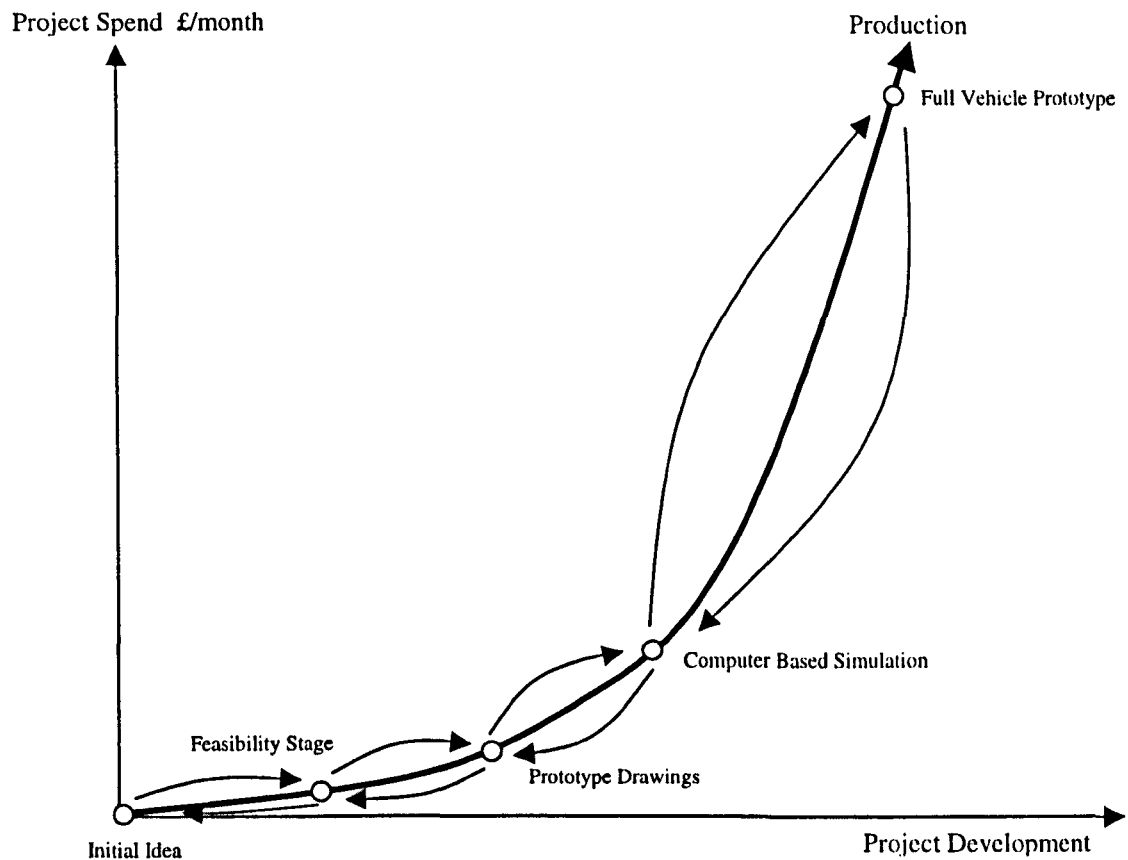
Development - ‘the process used to apply technical or scientific information and knowledge for product or process designs required to meet the needs of the organisation or its customers.’

### **2.2 Research Process**

Research can be undertaken from the body of knowledge through published material, through expertise held by members of an organisation, or through scientific or technical experimentation. As a part of the design process, prototyping is commonly used to enhance knowledge, and to improve the quality, speed and efficiency of the process and/or product [28]. Prototyping is classified as either analytical or physical prototyping [29]. Analytical prototyping is commonly manifested through computer based simulation, allowing a high degree of flexibility, but is based on current knowledge. Physical prototyping lacks this flexibility, but can detect unanticipated phenomena.

Within the Hybrid Vehicle Department, the research process has traditionally involved both forms of prototyping, using computer-based simulation to assist in predevelopment of a full vehicle prototype.

## 2.3 Cost of R&D



Adapted from Smith, P., and Reinertsen, D., *Developing Products in Half the Time*, 1991 [30]

*Figure 4. R&D Spend vs. Development Stage*

Figure 4 models this process of R&D in a generic manner, covering the range of activities undertaken within the department. The figure illustrates the high level of cost associated with a full prototype vehicle, compared to the earlier stages of the R&D process. The author has also included loops between project development stages, highlighting that R&D is not a continuous process, but an iterative one. Changes made on the full prototype vehicle can be seen to incur a high level of cost. This cost is both financial, and in terms of time. Thus, for this approach to be efficient, the knowledge

required to produce the full prototype must exist at the computer simulation stage. For example, the TETLEI project required a large number of changes to be made on the prototype vehicle, resulting in the project running both over time and over budget [31].

So changes and reiterations can be costly. But why have these reiterations at all? The reiterations represent learning, and the application of this learning to the improvement of the product or process [32]. For example, an area where knowledge is lacking may be identified by a problem encountered on the prototype, which was not considered in the initial design. This leads to a redesign, which incorporates the new knowledge to overcome the problem.

From the initial definition of research, it can be seen that this reiterative process is crucial in achieving the aim of acquiring knowledge. The cost of reiteration is offset by the knowledge gained. So to improve the research process, we do not aim to reduce the number of iterations, but to reduce the cost of these iterations. This of course assumes that in the initial instance, the information or knowledge required does not exist elsewhere in the body of knowledge (literature, personal experience) i.e. that the initial stages of the research process have been undertaken in a thorough manner.

If the cost of a full prototype is relatively low, or the current knowledge of an area is high, then we may consider the step from an analytical prototype to a full physical prototype to be acceptable. In terms of automobile prototypes, especially in the field of hybrid electric vehicles, system component costs are not insignificant. Hence a large gap exists between the prototype cost and the design/simulation cost.

## 2.4 Part Prototyping (PP)

Where a large difference in cost exists between analytical and full physical prototyping, an intermediate stage may be appropriate. A good example of this is in the field of vehicle aerodynamics. Conventionally, a scale model of a vehicle body is produced and tested in a wind tunnel [17]. This allows changes to be made rapidly and at low cost. Another method used in aerodynamics is to test a full-scale component of the vehicle in isolation, for example, a racing car wheel arrangement [33]. These intermediate stages are termed 'part prototypes' by the author. They are used to investigate specific areas in order to obtain information and knowledge to support development of a full prototype. The example of aerodynamics highlights that the body of knowledge must be constantly reviewed, and cannot be considered static. In the field of aerodynamics, computer based simulation (Computational Fluid Dynamics, CFD) is progressively replacing the traditional physical modelling approach [34].

A part prototype approach is illustrated schematically in Figure 5. One or a number of relatively low cost part prototypes may be used to generate the required knowledge. Iterations still exists between the project stages, but ideally the bulk of these iterations are conducted at a lower cost. Part prototypes may even replace a full prototype, depending on the information or knowledge required. If a full prototype is required, some reiterations with this are still likely, as the knowledge obtainable from the part prototype cannot be the full knowledge gained from the full prototype (if it were, the purpose of the full prototype must be questioned). However, these costly iterations should be reduced in number through application of knowledge gained from the part prototype.

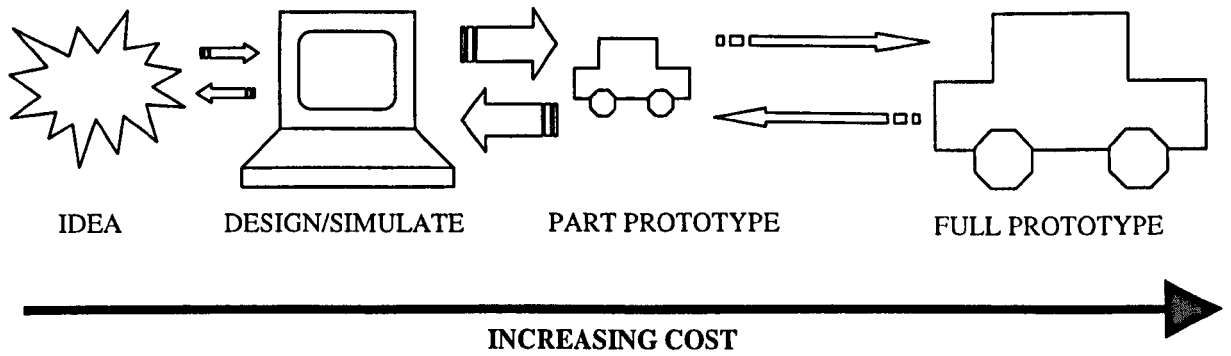


Figure 5. Improved R&D Process

This approach may be considered analogous to the full prototype becoming the product, and hence the part prototype is a prototype supporting development of that product. Identification of the requirement for a part prototype can thus be considered analogous to the requirement criteria of a product prototype. From [29], *'Products which are high in risk or uncertainty, due to high costs of failure, new technology, or the revolutionary nature of the product will benefit from prototyping'*. The risk may be considered as a business risk, or even in the case of a safety related system, a physical risk to human health [35].

The part prototyping approach is supported in [29], which identifies that prototyping can be used to reduce the risk of costly iterations, and that the risk associated with these iterations must be balanced with the time and expense incurred through the production of a prototype. When considering a part prototype, this balance effectively represents a placement of the part prototype between analytical simulation and the full prototype, such that the knowledge gained is maximised, and the cost minimised.



## **2.5 Hardware-in-the-Loop as a Part Prototyping Approach**

If knowledge has an associated cost, then ideally the part prototype only contains the information or knowledge the researcher is seeking. Using HIL simulation, current information and knowledge can be captured through simulation on a computer-based platform, and integrated with the physical part prototype. This potentially offers cost savings in the capital cost, the development time, and the operational time of the part prototype. Changes can be made rapidly in the software environment to known areas of the system in order to establish their effect on the unknown areas.

For example, in the field of automotive engineering, HIL simulation is used in the development of braking system technology. In [36][37], the system inputs (accelerator, brake and steering) are either generated by a direct human input, or a recorded drive cycle. The inputs are processed in software, along with a model of the vehicle dynamics based on current knowledge. A brake actuation signal is generated and fed to a physical braking system attached to a dynamometer. A measured wheel speed is then fed back to the software for inclusion in the brake control algorithm. This application of HIL and prototyping is appropriate given the safety-related nature of a brake system. The ability to automate the system inputs facilitates greater test repeatability.

## **2.6 Conclusions**

In conclusion, the author has identified that in the development of a product or prototype, an intermediate prototyping stage should be considered when the product or prototype is:

- Expensive to construct.
- Expensive to run.
- Safety related in its operation.
- In a new area where current knowledge is limited.

### **3 Research Method**

The research method adopted by the author is a systematic design approach, as described in [38]. This section details the identification of a need for a part prototype (PP), and the selection of an appropriate PP for the Hylander project.

#### **3.1 Requirement for a Part Prototype**

The requirement for a tool other than a pure mathematical modelling approach was presented to the author at the instigation of the Hylander project. The author examined the Hylander project in the context of the general R&D process. The author concurred that a part prototype for the development of IWC strategies was required in the Hylander project because:

- The Hylander vehicle represents a large investment (currently £402,000) [39].
- The operational cost of the vehicle is high relative to analytical simulation, requiring two engineers to operate the vehicle and the uses of resource i.e. test track facilities.
- The IWC operation of the Hylander vehicle has safety implications.
- Limited knowledge exists in the field of off-road tyre/terrain behaviour, especially in the area of IWC.

These facets can be directly converted into a list of requirements for the part prototype:

- The PP project should be low cost; (the financial budget of the PP project is £5,000 for capital goods, excluding software and HIL simulation tools).
- The operational costs associated with the PP should be minimised.
- Operation of the PP should not have significant safety implications.
- The PP should inherently contain the knowledge of the tyre/terrain interface and its effect on an IWC vehicle.

### **3.2 Concepts**

A number of initial concepts for the PP were generated between the author and the project customers (limited to the Hylander development team [26]), covering the range from pure simulation to a full-scale physical prototype (i.e. the Hylander vehicle itself). These concepts are listed in table 1, along with basic estimates of their relative cost (build cost + operational cost) and potential benefit (amount of knowledge which can be gained).

The next stage in the part prototyping process is the selection of an appropriate PP, based on the cost/benefit relationship in the context of the required knowledge, and the PP requirements.

Concepts	Description	Cost	Benefit
1. Full vehicle	Hylander vehicle	V. HIGH	V. HIGH
2. IWC system + HIL	Drivetrain and other non-IWC related systems are mathematically modelled as required.	HIGH	HIGH
3. Single wheel + suspension + HIL	Response of a single wheel is characterised for varying terrains. The vehicle dynamic response and drivetrain systems are mathematically modelled. Variations in terrain between wheels modelled by some means.	MED/HIGH	LOW/MED
4. Scaled full vehicle	As 1 but scaled	LOW to HIGH (depending on scale used)	HIGH
5. Scaled IWC system + HIL	As 2 but scaled	LOW to HIGH	MED/HIGH
6. Scaled single wheel + suspension + HIL	As 3 but scaled	LOW to HIGH	LOW/MED
7. Computer simulation	Complete vehicle and terrain mathematically modelled using current knowledge	LOW	LOW

Table 1. Part Prototype Concepts

3.3 Part Prototype Selection

In the context of the Hylander vehicle, the capital cost of electrical system components represent a large proportion of the whole vehicle cost. Motors and power electronics are particularly amenable to scale modelling, as their size-weight to power ratio is consistent (for a given form of motor). However, smaller motors are mass-produced, where as traction motors suitable for vehicles tend to be individually made. Thus, smaller motors are disproportionately cheaper. The spread of cost as a function of the scale is illustrated in a generic manner by the shaded area in figure 6. The knowledge gained from a scaled approach is fairly independent of scale. However, in order to produce a scaled model, relaxations or approximations may have to be made to limit the

development time and cost [17]. Thus the benefit of a scaled approach is shown as being slightly less than the corresponding full scale approach. Given the relatively small budget available to the project, a scaled approach was selected.

Analysis of the wheel/terrain interaction [40] shows it to be a function of the terrain, the tyre/wheel, the suspension, and the vehicle geometry. The vehicle drivetrain provides operational limits, but does not directly affect the vehicle dynamics. As drivetrain modelling is well understood, there is no requirement for a part prototype to model this. Thus a scaled full vehicle prototype is not required and a HIL based approach is appropriate.

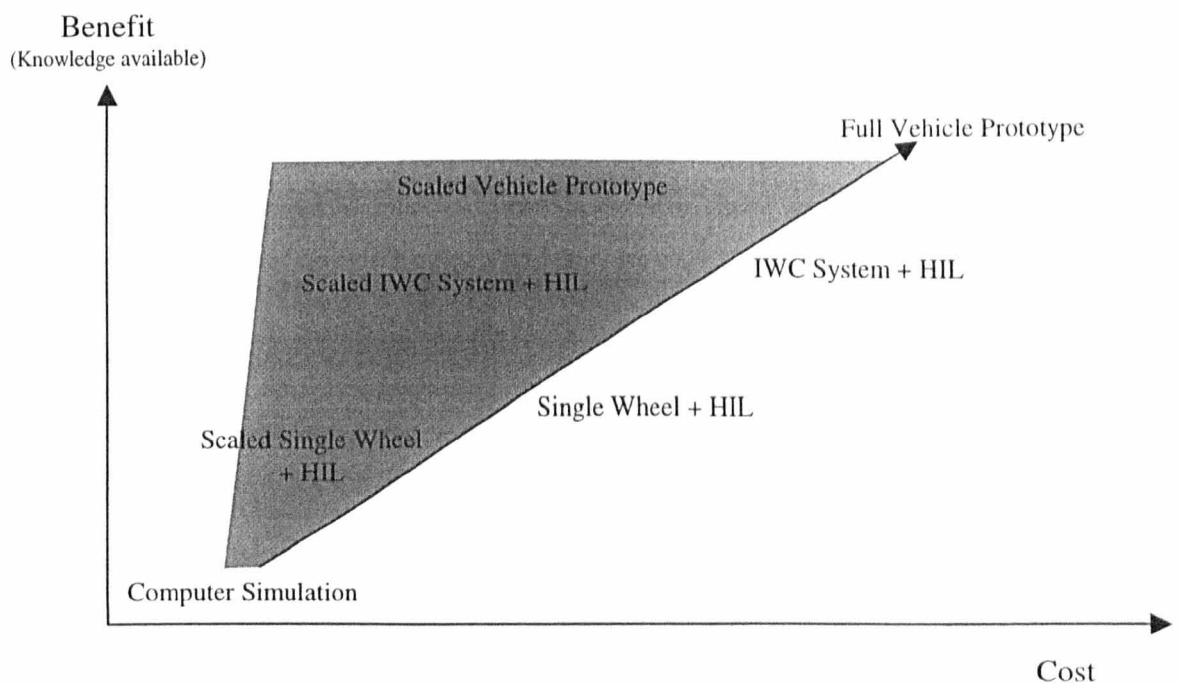


Figure 6. Generic Schematic of Cost/Benefit Relationship for PP Approaches in Hylander Project

A single wheel modelling approach will require the vehicle dynamics to be contained in the computer simulation element of a HIL simulation. Although knowledge is available, this approach does not inherently incorporate the interrelationships between IWC

wheels. Also actuators would be required to mimic the effects of the vehicle on the wheel, adding to the complexity and cost associated with this approach.

Hence a scaled part prototype of the IWC system using HIL simulation was selected as an appropriate tool for the development of IWC. The terrain, wheels, tyres, suspension, and physical layout are physically modelled. In order to provide dynamic analysis of IWC strategy operation, motors are incorporated with appropriate gearing to drive the wheels.

### **3.4 Choice of Scale Factors**

The choice of appropriate scaling factors is based on the process of dimensional analysis [17]. The appropriate factors are determined using current knowledge relating to vehicle dynamics and terrain classification. Although unknown phenomena may prevail, the fundamental laws of physics govern these phenomena. Hence, through modelling of the main physical characteristics of the system, it is predicted that the system will operate in a representative manner.

Scaling factors are characterised as primary and secondary factors. The primary factors are specified, and the secondary factors derived from them. For this work the primary factors chosen were length, mass and acceleration. Acceleration is scaled 1:1 as gravity cannot be altered. From these factors, appropriate scaling of secondary factors such as force, torque, damping etc. were derived [38].

The choice of an appropriate scale factor for length and mass was made using a spreadsheet. As a rough approximation, considering material density as a fixed element, the mass scale is estimated as a function of the length scale.

This approach highlighted:

- An onboard driver would be too heavy, hence remote operation is required.
- Required torques reduce with size, along with material requirements. This implies that a smaller scale represents lower cost.
- Too large a length scaling factor will produce a model which is too small to carry unscalable (physical size) on-board equipment e.g. instrumentation, electronics.

The chosen length scale factor is 8 (i.e.  $1/8^{\text{th}}$  scale model), chosen due to these considerations, and due to the commonness of the scale in hobby based vehicle scale modelling. The choice of mass scale factor was based on an estimate of the model mass from preliminary design, and the torque capability of the motors (mass scale factor equals 400).

### **3.5 The Part Prototype Research Tool – Hylander Scale Model System**

The author designed, developed, built and tested the scale model system. The HIL simulation is implemented using an industry standard tool, dSPACE<sup>TM</sup> that operates with the MathWorks Simulink<sup>TM</sup> environment. Using the MathWorks Real-Time



Workshop™, software developed in Simulink™ is auto-coded onto the dSPACE™ platform for operation in real-time. This process is discussed in detail in [20].

The physical scale model is illustrated in figure 7 in the context of the complete scale model system. The physical scale model represents the wheels/tyres, driveshafts, axle gearboxes, motors, motor controllers, axles and body of the Hylander vehicle. in scaled form. The motor controllers could have been implemented in software using the dSPACE™ platform. However, this would have imposed an undesirable overhead on the processing time of the software system.

Also, implementing physical motor controllers allows the software element of the system to incorporate only the IWC strategy, and a signal-processing framework into which the IWC strategy is inserted. This framework incorporates signal filtering and a steady state characterisation of the motor controllers, motors and drivetrains, used to generate appropriate output demands to each of the motor controllers for the required wheel torques [40].

A potential advantage of this approach is the ability to implement this software element of the system directly on the Hylander vehicle. However, this raises issues of code reliability and requires the operation of the scale model to be validated against the Hylander vehicle. As the Hylander vehicle build is incomplete, the scope of use of the scale model system is limited to conceptual IWC strategy development i.e. developing IWC ideas for the Hylander vehicle at a strategic rather than an implementation level.

The host PC is used to monitor and log system variable values through the dSPACE™ graphical user interface (GUI) software packages, TRACE™ and COCKPIT™. The

host PC can also be used to generate, or record and reproduce driver inputs. This facilitates greater reproducibility of test regimes, and allows direct comparisons to be made between computer based and HIL simulation results for a given input schedule.

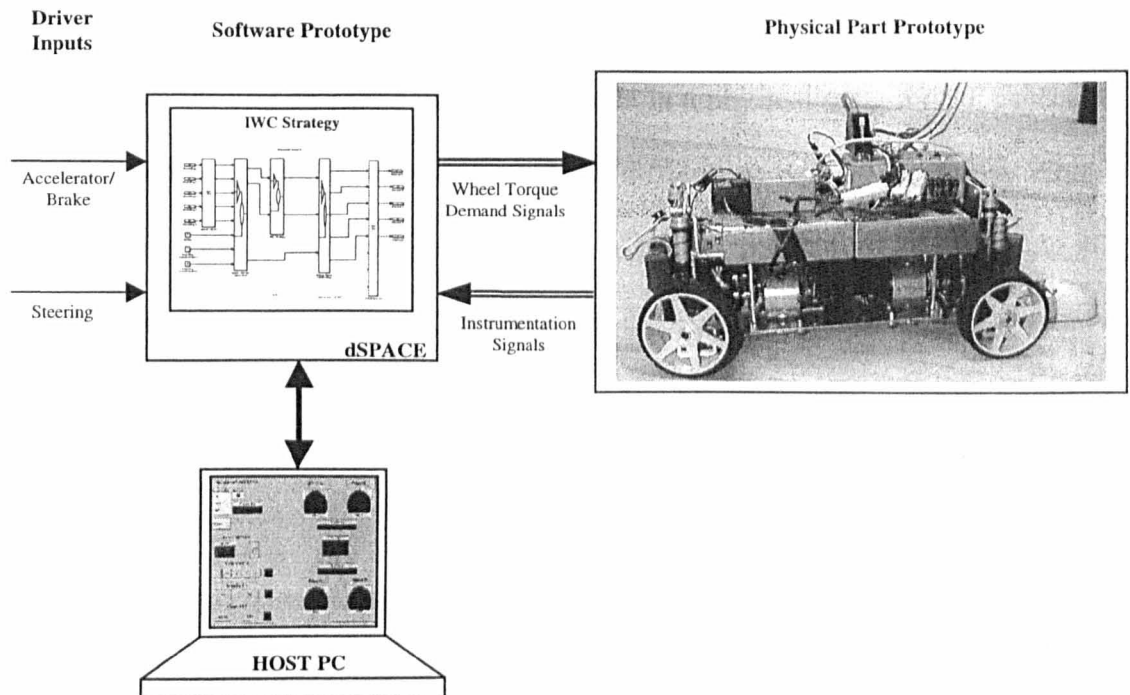


Figure 7. Hylander Scale Model System Schematic

On board instrumentation provides wheel speeds, vehicle speed, axle positions, and yaw rate measurements. These are suitable for IWC strategy development. Where possible, this instrumentation corresponds with the instrumentation used on the Hylander vehicle.

A key issue in the development of a physical scale model is deciding what relaxations are appropriate in the model's representation of the full-scale object. These are made with respect to the area of knowledge required. For example, in order to assess IWC strategies, there is no need for the physical scale model to look like the Hylander vehicle. In the build of the physical scale model, some areas which will affect vehicle

dynamics were not included in the model specification e.g. wheel castor, wheel camber. The effect of this simplification cannot be determined until the Hylander vehicle build is complete and back to back validation is undertaken. In the same light, accurate modelling of these factors is not possible until the vehicle build is complete, as the vehicle axles are heavily modified compared to a conventional vehicle. Knowing where to draw the line on which factors to include in a physical scale model, especially in an area where limited knowledge exists, is difficult to achieve, and may require reiteration between the development and validation of the physical scale model. In this instance, a generic approximation has been made for the castor and camber angles.

Focusing on the role of the scale model system, given that generic approximations have to be made in the development of the physical scale model, a more generic approach for predevelopment purposes may be appropriate. Thus the system is used to investigate a concept, rather than to model the product or prototype directly. For example, a physical vehicle model could have been produced to investigate IWC strategies, rather than to investigate the manner in which the Hylander vehicle will respond to IWC strategies. Again a trade-off is made between benefit and cost.

### **3.6 Conclusions**

The author has generated a requirements specification for a part prototype to support development of IWC strategies in the Hylander project based on the criteria listed in section 2. A number of concepts have been evaluated and an approach using an 8<sup>th</sup> scale physical model of the Hylander vehicle IWC system in a HIL simulation has been developed.

This approach meets the initial requirement specifications:

- Capital cost of the system is low compared to the Hylander vehicle (see section 6.1).
- Using the HIL simulation technique, tests can be automated, reducing the time and hence cost associated with operation.
- The application of remote operation provides a non-safety-related manner of operation. Also, the scaled approach has reduced energy levels in the system, and through this, reduced safety implications, e.g. reduced kinetic or electrical energy to dissipate in the event of an impact or electrical short respectively.
- The scale model system inherently incorporates knowledge of the operation of IWC on a terrain. However, no physical feedback is provided to the system operator. This represents the primary gap in benefit (knowledge) between the part prototype and full prototype. This limitation is offset by the relative cost of the scale model compared to the Hylander vehicle. This is discussed further in section 6.1.

Another identified limitation of the scale model system is the scope of use. As the Hylander vehicle build is incomplete, validation of the representability of the scale model compared to the full-scale vehicle cannot be undertaken. Hence, the effect of phenomena which are not accurately modelled (e.g. castor and camber) cannot be verified. Thus, the scale model currently exists as a trendwise approximation of the Hylander vehicle. As such, its scope of use is limited to conceptual development of IWC strategies, rather than for tuning of strategies for direct application on the Hylander vehicle. This reflects a limit on the knowledge obtainable from the physical scale model at this time.

## **4 Main Research**

The main research represents an application of the Hylander scale model system in the development of an IWC strategy to support the Hylander project.

### **4.1 Aims of the Main Research**

The aims of the main research are:

- To test the limits of the Hylander scale model system in a complex closed loop control application containing oscillatory, transient dynamics.
- To provide a case study example of the IWC strategy rapid prototyping process.
- To improve the IWC rapid prototyping process through the application of lessons learnt in its implementation.
- To develop an IWC strategy which will operate the Hylander physical scale model in a manner representative of a conventional 4x4 vehicle with a diesel engine, 5-speed gearbox, transfer box and lockable centre differential.
- To relate lessons learnt through development of a complex closed loop IWC strategy on the scale model to its application on the full-scale vehicle.

## 4.2 Scope of the Main Research

The scope of the main research undertaken within the portfolio is to support the Hylander vehicle project at a predevelopment, or concept investigation stage through the development of an IWC strategy which operates the Hylander physical scale model in a manner representative of a conventional 4x4 vehicle (Land Rover Defender 90).

The work is limited to concept investigation as the build of the Hylander vehicle is incomplete. In the role of concept development, the model is utilised to test generic IWC strategy ideas. Development of these ideas is undertaken at a strategic, rather than a tuning level.

The selection of an IWC strategy to mimic the operation of a conventional 4x4 vehicle is taken from a research plan developed by the author, based on the ideas and requirements of the customer [38]. This strategy is part of a research development plan to demonstrate the ability of the Hylander vehicle to emulate a number of conventional drivetrain arrangements.

The research plan also identifies that the operational conditions under which the strategy is evaluated must also be specified. This initial work is scoped for use on flat, uniform terrain.

### 4.3 Innovation in the Main Research

The main research is the application of a **physical scale model** in a **HIL simulation** for the development of an **IWC strategy**, reproducing the **behaviour of a conventional 4x4 drivetrain**. The author has highlighted the four key areas to the research. In order to justify the innovation in this research, the author will demonstrate that previous work (cited by reference from literature) in the four key areas differs from the main research. For clarification purposes, the main research is henceforth referred to as the 'MR'.

The scope of reference is limited to ground vehicle applications, primarily in the automotive industry as this is the area in which the MR has been undertaken. This is appropriate due to the specific nature of the application, i.e. modelling a 4x4 drivetrain. Each of the four key areas is investigated in turn.

**Scale modelling** has been applied in a number of areas, but most commonly in the field of aerodynamics and hydrodynamics [17] for aircraft, boats and automobiles. The use of a physical scale model to investigate off-road traction is described in [41] for a 'marsh buggy'. This work focuses on the correlation between results from the scale model and the full-scale vehicle. This work differs from the MR as a scale physical model of an existing vehicle is produced, rather than supporting the development of a new vehicle. In [42], a scale model is used to support the development of a full-scale vehicle, much in the same manner as in the MR. The vehicle is a lunar rover, used in the later Apollo missions to the Moon. Scaling associated with both the terrain and the vehicle characteristics is considered, but unlike the MR, consideration is not given to control development applications.

**HIL simulation** techniques have been applied widely in the automotive industry, commonly for either validation purposes, or in the rapid prototyping of control systems. Validation of the operation of production ready Electronic Control Units (ECU) using HIL simulation and the dSPACE<sup>TM</sup> product is described in general terms in [43]. This paper also highlights a specific application in the development of a clutch control unit [44]. Other applications where ECU validation is undertaken using HIL simulation include Rover Group [45] and AUDI Group [46] projects investigating engine control unit validation, and projects looking at brake/traction systems development [37] as described in section 2.5 of this report. These applications differ from the MR, as they do not consider the application of the HIL approach to control strategy development.

The application of HIL as a rapid control development tool is discussed in general terms in [20]. Specific applications for the development of engine control systems [18], braking/traction control systems [47], and door electronics control [48] can be found in the literature. These projects use HIL simulation in a similar manner to the MR. However, the specific fields of application are different, and only full-scale system components are considered.

More specific to the field of hybrid electric vehicles, HIL simulation has been applied to the development of a drivetrain control system [49]. This work differs from the Hylander project where control system development for the drivetrain is undertaken in computer based simulation, and the MR utilises the HIL approach to develop a control system for IWC.

**IWC strategy** development is discussed in the context of computer based simulations in [50][51], which consider generic vehicle concepts with four wheel steering and four



wheel IWC. Other work [23][24], utilises computer-based simulation to investigate the concept of IWC for a vehicle with no mechanical steering mechanism, providing vehicle yaw through the application of a torque difference between the left and right hand wheels.

Practical applications of 4 wheel IWC have been considered using a conventional drivetrain and four clutch arrangements to limit the torque delivered to the wheel [52]. A similar approach has also been adopted for a 2WD (Wheel Drive) vehicle [53]. Such arrangements differ from the concept of IWC used in the MR as they can only vary wheel torque between zero and a maximum value determined by the engine torque limits, rather than possessing the capability to provide opposing torques.

Practical applications of IWC for 2WD vehicles using electric motors are considered in [54] at a physical system level, and in [55] at a control level. Although some analogy can be made with the work contained in the MR, these applications do not consider the potential of a full 4WD approach.

A 4WD vehicle, with the front wheels mechanically linked to the engine in a conventional manner, and the rear wheels driven by two separate motors providing rear wheel IWC is described in [56][57]. This represents the closest approach found by the author to a full-scale vehicle with 4WD IWC, which provides details of method of control. The approach has been adopted to improve vehicle dynamic behaviour when influenced by a lateral disturbance e.g. side winds. The author has found reference to a military HUMMER vehicle using four independent electric motors to provide IWC [16]. However, the author has not found any reference to the manner in which this vehicle is controlled.

A common feature of the literature relating to IWC development is that it focuses on the use of IWC to alter [23][24][25] or ‘improve’ vehicle behaviour [55][56]. This differs from the approach of the MR, which aims to reproduce the behaviour of a conventional vehicle prior to improving or supplanting it.

**Mathematical modelling of a conventional vehicle drivetrain** is usually developed to investigate specific phenomena. For example, in [58] a drivetrain model is produced to evaluate the effects of various clutch control approaches. In this example, the mathematical model of the drivetrain is simplified based on assumptions made in line with the scope of investigation. These simplifications include the consideration of a ‘lumped’, single wheel drivetrain i.e. the four wheels are represented by a single wheel, modelled with appropriate properties. This approach reduces the complexity of the mathematical models, and hence the development time associated with their generation. However, such an approach would not be feasible for the MR, as individual torque demand signals are required for each wheel.

Thus the mathematical model of a conventional vehicle drivetrain developed in the MR is a specific approach, appropriate to the MR application. The approach used is built upon prior literature as described in [59]. The main difference between the MR mathematical models, and the literature used was in the development of a model of a lockable differential gearbox, undertaken from first principles.

To this point the focus of this section has been on work undertaken in prior literature in each of the four main areas which constitute the research. The remainder of this section considers literature that describes applications that cover two or more of the constituent areas of the research.

The application of a mathematical model of a conventional vehicle drivetrain, implemented as the software element of a HIL simulation is described in [36] and [60] for the application of ABS and traction control development. In [36] the brake system is reproduced as a physical element in full-scale, differentiating it from the scaled work of the MR. In [60], mathematical models of the vehicle are applied in software as the control system plant, and HIL used to test the operation of a physical ECU controlling the braking system. The vehicle is modelled using the ADAMS<sup>TM</sup> dynamic simulation package to evaluate the effect of the brake system on the vehicle dynamic operation. This approach demonstrates the potential for future work to prototype the off-road behaviour of the Hylander vehicle through analytical simulation. However, this work differs in approach to the MR, as it is limited to consideration of on-road conditions only. The software currently imposes this limitation.

The application of a physical scale model in a HIL simulation for the study of IWC strategies is described in [61], covering three of the key areas of the MR. The physical scale model used in this work has four independent electric motors driving the wheels, and both front and rear wheel steering. Wheel encoders are used to provide wheel speed feedback. The scope of use of this vehicle is defined in the work as being for the development and test of ABS and integrated chassis controller strategies. The model is run on a treadmill, which represents a smooth road surface.

The work differs from the MR in a number of key respects:

- The modelling approach adopted is generic in that it does not directly represent a particular vehicle, but is a trend-wise approximation of vehicle dynamic behaviour.

- The work describes the development of a control strategy aimed at improving the lateral dynamic behaviour of the vehicle for an automated highway application i.e. on-road rather than off-road.
- The work describes the development of a control strategy to improve the dynamic behaviour of a vehicle, not to reproduce the behaviour of a conventional vehicle drivetrain.

It should also be noted that this work was published in June 1998, towards the end of the MR period. This highlights the timeliness of the approach used in the MR.

In figure 8, the author has generated a Venn diagram highlighting how the previous work (cited by its reference number) identified in this section has addressed the four key areas of the innovation. From the figure, the potential for innovation is highlighted.

Previous work undertaken in the area of IWC has focused on improving the dynamic behaviour of a vehicle. This is to be expected, as the potential benefits of IWC can be easily demonstrated in this manner. This has left a gap for innovation in the application of an IWC strategy operating the vehicle in a manner representative of a conventional vehicle. It is this specific application that provides the innovation.

From the review of work in the key areas of the research it has also been highlighted that prior work has focused on on-road, rather than off-road vehicle operation. As the main research undertaken within the doctorate has only considered an on-road application, this is not included in the claim of innovation for the work. However, the scale model system has been designed to be appropriate for off-road vehicle applications.

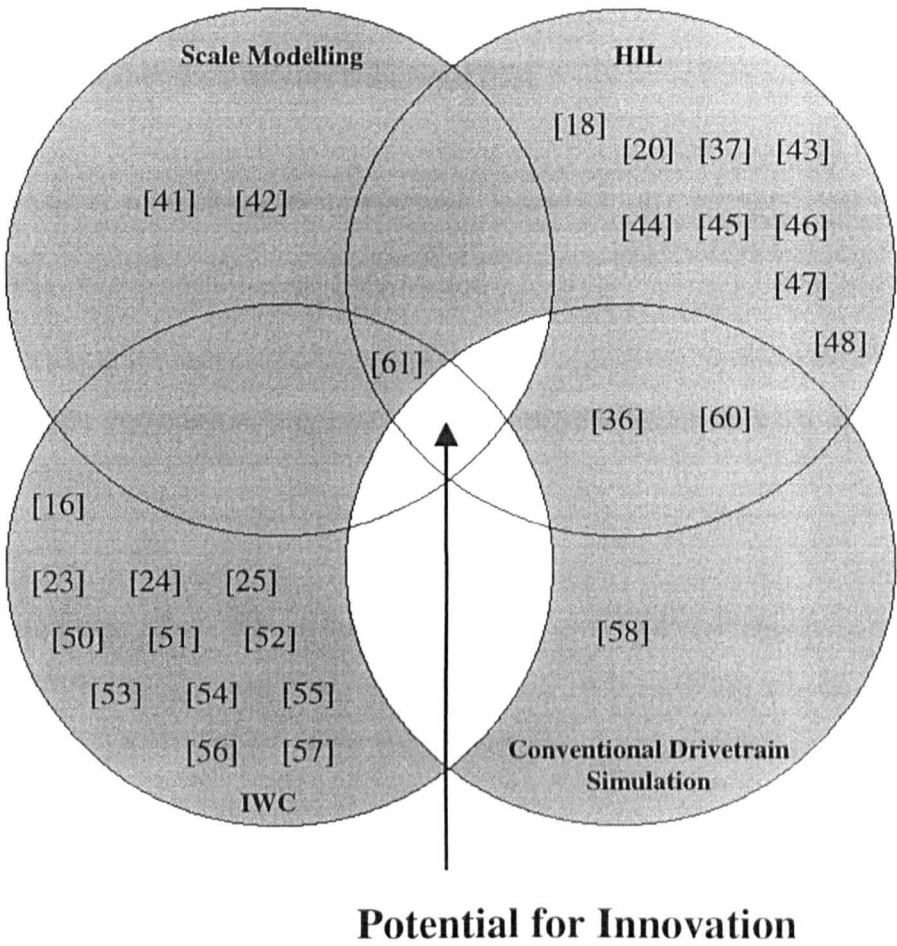


Figure 8. Venn Diagram Highlighting Opportunity for Innovation

The gap in the literature is primarily due to the nature of the work undertaken in the field of IWC. As much of the work has been undertaken in an academic context, or to address a specific phenomena e.g. lateral stability, the focus has been on demonstrating the potential benefits of IWC.

The application of IWC within the industrial context of the Rover Group requires a more subtle approach to be adopted. Practical considerations make it prudent to initially develop a control strategy that mimics the behaviour of a conventional vehicle, and to develop from that platform. This approach is based on the desires' of the customer, who expressed concerns about introducing large step changes in vehicle behaviour at an

early stage of the vehicle development, especially if the changes would require the vehicle driver to alter their driving behaviour [62].

The approach of mimicking the operational behaviour of a conventional vehicle also offers other practical benefits, such as;

- The vehicle operation acting as a conventional vehicle can be used as a baseline of performance.
- A requirement of the Rover Group is that all prototype vehicles possess a current MoT certificate. Conventional vehicle operation will facilitate the vehicle obtaining this, acting in a manner the tester will expect.
- No special knowledge will be required to operate the vehicle. Hence, senior management can test the vehicle in a practical manner.

From the identified potential for innovation, and the main research undertaken, the author's claim of innovation is:

**‘The application of a physical scale model representative of a prototype vehicle, in an automotive manufacturer R&D project, to the development of an IWC strategy, operating in a manner representative of a conventional 4x4 vehicle, using HIL simulation techniques.’**

## 4.4 Creating the Application

From the initial expressed desire to reproduce the behaviour of a conventional 4x4 vehicle, the author extracted specific requirements from the customer and developed these into an engineering specification. This specification highlights the components of the drivetrain to be reproduced, and the relevant effects to be modelled. Only phenomena that are physically discernible to a driver are considered.

The conventional drivetrain of a Defender 90 vehicle is illustrated schematically in figure 9. The boundary between controller and plant represents the boundary between the elements of the drivetrain modelled in software, and the physical elements represented by the scale model in HIL simulation.

The output of the IWC controller is a torque demand to the wheel, and wheel speed is fed back to the controller. The controller inputs are a torque demand from the driver, representative of the accelerator position, a gear selection (1-5), transfer box state (low/high), and centre differential state (locked/unlocked). No clutch pedal exists on the Hylander vehicle, so the effect of a clutch in the gear change procedure is represented in the controller.

The scope of the work looks at forward gear states only, and considers neutral and reverse as separate operational modes. The Hylander vehicle utilises the same brake system as a conventional Defender, so this is not modelled either in software, nor hardware (physical scale model). The effect of a braking system on the operation of the controller can be established through artificial restraint of the wheels.

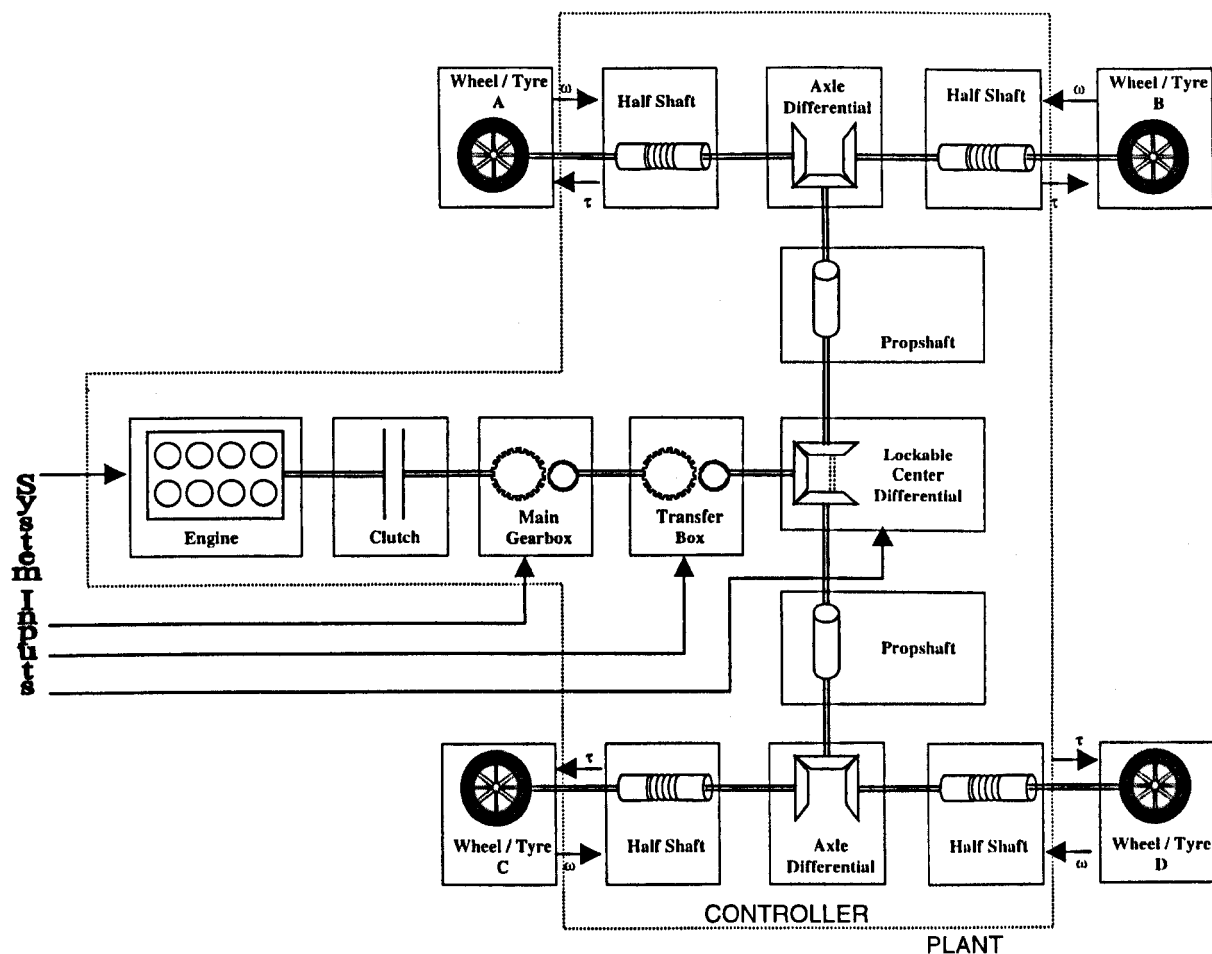


Figure 9. Defender 90 Drivetrain Schematic

A transient, oscillatory element is included in the IWC controller, implemented through mathematical modelling of the half shaft compliance. The requirement for an oscillatory response limits the margin of stability available to the system, and thus provides an acid test of the controller operation.



## 4.5 Implementing the Application

There are three stages to the implementation of an IWC strategy on the scale model system:

1. **Non-Real-Time Off-Line Full-Scale Simulation** - mathematical models of a full-scale vehicle drivetrain are implemented in a computer-based simulation with a simple vehicle model acting as a plant. The results are validated against literature [63], manufacturer's data [64] and expert opinion [65] (appropriate for conceptual development). The features of operation required by the customer are verified at this stage in the implementation. Once validated and verified, the results of this stage provide the measurement against which the scaled stage results are validated.
2. **Non-Real-Time Off-Line Scaled Simulation** – the system variables are scaled using scaling factors appropriate to the Hylander physical scale model. The computer-based simulations undertaken in the previous stage are repeated using these scale values. This facilitates validation that the correct scaling factors have been applied, and can identify any phenomena associated with the scaling process. Once validation has been completed successfully, these scaled, off-line simulation results are used as a measurement against which the results of the HIL simulation stage are validated. This provides a link between the operational behaviour of the full-scale vehicle and the scale model system.
3. **Real-Time HIL Scaled Simulation** – the computer simulation based vehicle plant model is replaced by the physical scale model of the Hylander vehicle. The drivetrain (IWC controller) is coded onto the dSPACE<sup>TM</sup> platform and operated in

real-time. System operation is monitored using the COCKPIT™ and TRACE™ software tools. This stage validates that the system models used in the computer based simulations are representative, and if not, identifies areas for further research. Operation under conditions, which are difficult to mathematically model, can also be facilitated e.g. off-road conditions.

In this report the author will focus on a single set of results, which demonstrate the key learning points from the implementation. In order to ensure that the operation of the system is repeatable, i.e. that the expected response is obtained under a variety of conditions, a number of other tests have been performed. These tests are limited to the operational scope of the application, i.e. flat, smooth terrain. Repeatability under a number of different terrain conditions is a key issue in the development of IWC for the customer, and thus has been deemed to represent specific stages in the IWC strategy development process [38]. The author has tested the system in all of the operational modes of the controller (main gearbox gear states, transfer box gear states and centre differential state), and with extremes of input values. These tests have demonstrated the repeatability of the system [59].

In this work, for all stages of the process, a test regime was devised based on the operational behaviour of a driver accelerating from rest and performing a first to second gear change. This input regime or profile indicates many of the characteristics of the drivetrain [58]. As the scope of operation is analogous to on-road driving, the centre differential and transfer box states are unlocked and high respectively. The input profile is illustrated graphically in figure 10 as the driver torque demand (representing the position of the accelerator), and the main gear ratio selection.

## 4.6 Results of the Implementation

The off-line simulation stages of the process highlighted a number of issues relating to the application of the scale model system, as discussed in [59]. Figure 10 illustrates the results of applying the test regime in an off-line, full-scale simulation. These results formed one of a number of results presented to the customer, demonstrating the predicted operation of the system.

From figure 10, key elements in the system are illustrated, starting with the two driver inputs and working from the driver, along the drivetrain through to the vehicle. The primary system variables are torques (output of IWC), and speeds (feedback from wheels). The driver-input profile (torque demand) incorporates the effect of a driver using a clutch to change gear through the driver removing torque demand to the engine during the gear change procedure. The effect of a clutch is modelled by a lag on the main gear ratio, smoothing the change between gear ratio states.

The engine torque illustrates the effects of engine overrun when the driver demand drops to zero. The gearboxes add no dynamic effect to the results, simply scaling the engine speed and torque, and hence are not included in figure 10. As the off-line simulation only considers straight-line motion, the differential gearboxes do not affect the results, and are similarly not included.

Variations between the engine speed and wheel speed (gearing aside) demonstrate the effect of compliance in the half-shafts. This introduces oscillatory behaviour into the system, which can be seen clearly at the time of the gear change (3.5 seconds). The oscillatory shaft torque represents the output of the IWC controller.

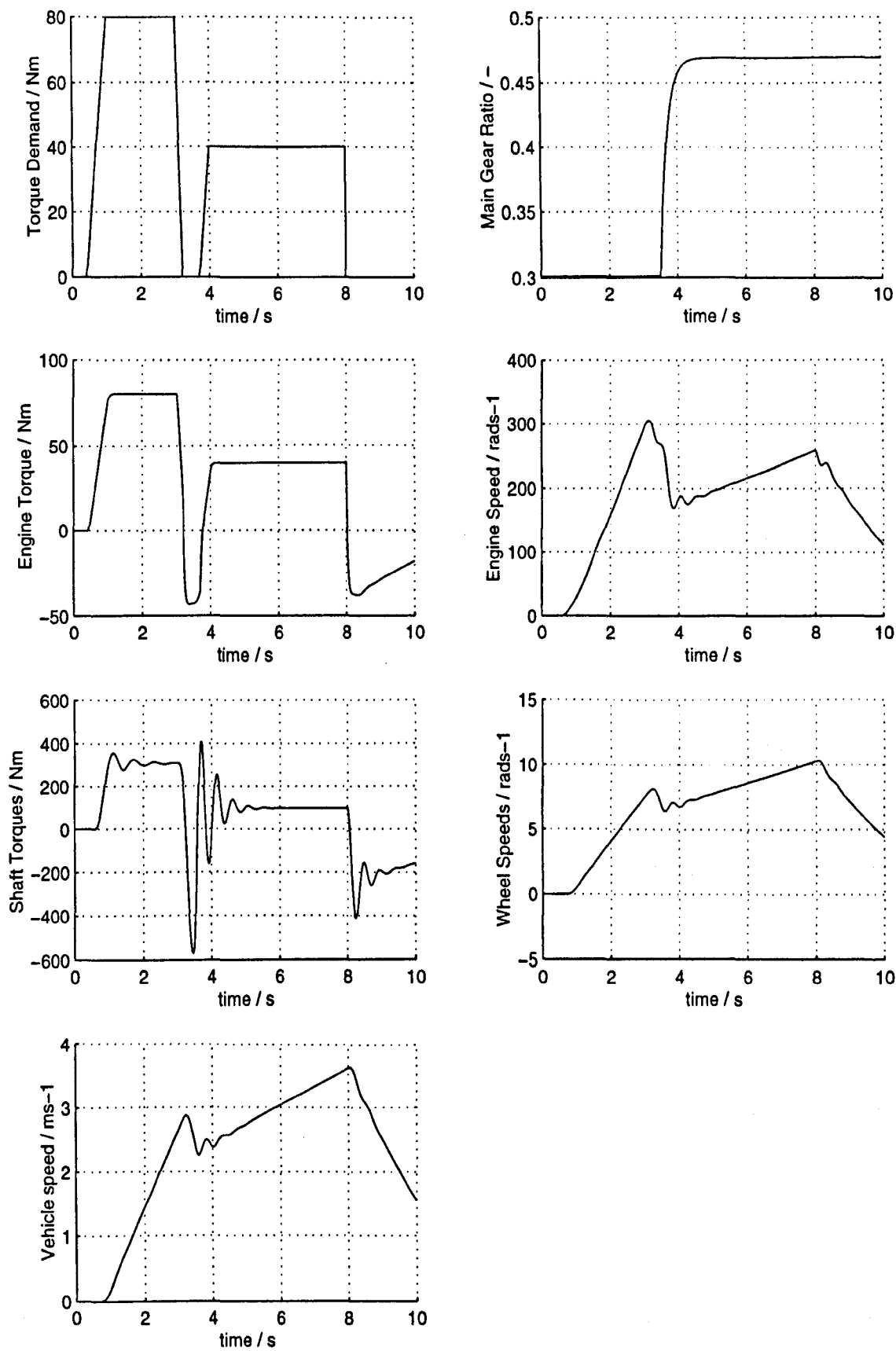


Figure 10. Results of Off-Line Full-Scale Simulation

The plant (vehicle model) feeds back wheel speeds to the IWC controller. Vehicle speed is also included in the figure as this is used as a comparison against manufacturer's data (standing start acceleration times, [64]).

Once the IWC controller operation had been validated as representative of a conventional 4x4 drivetrain, and verified as meeting the customer requirements through the off-line simulation results, the scaled representation of this controller was implemented. Results of this second stage of the implementation process are illustrated in figure 12 (off-line results) in section 4.7 of this report. From these results, scaling of time can be seen to cause the scale model system to run at higher frequencies. This raises potential stability issues in relation to the maximum sample rates of the controller [59].

The final stage of the implementation process is the application of the IWC controller on the physical scale model in a HIL simulation. As the physical scale model was operated in an enclosed space, the wheels were initially suspended to prevent damage to the physical scale model in the event of unpredictable behaviour. Figure 11 illustrates the output torque demand of the IWC controller and the wheel speed measurements taken from the physical scale model in the HIL simulation. These results were obtained using the same input regime as the off-line simulations. Some measurement noise effects can be seen on the average wheel speed signals.

From the HIL simulation results, the system can be seen to be unstable in operation. The HIL simulation results do not correlate with the predicted results from the off-line simulations, and hence do not meet the customer's requirements.

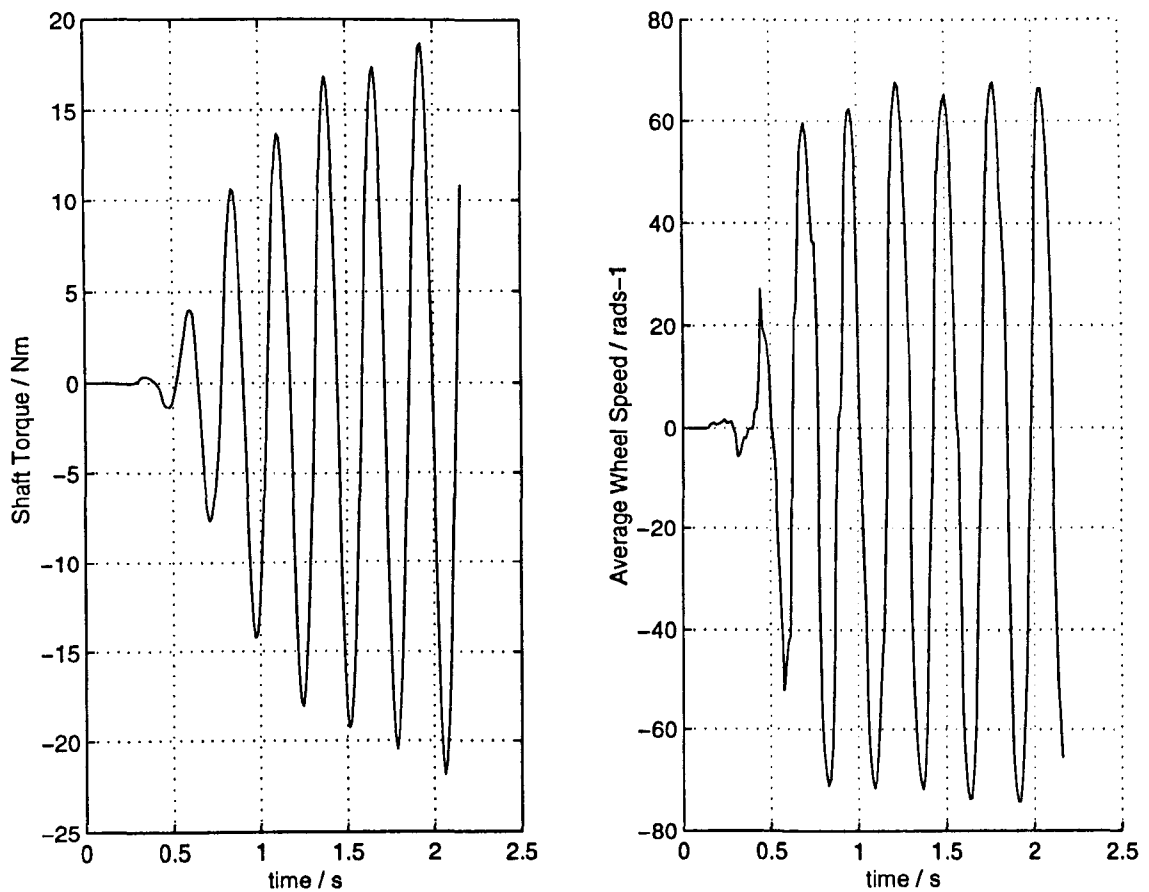


Figure 11. Initial HIL Simulation Results

## 4.7 Discussion

### 4.7.1 Improving Knowledge of the System

The discrepancy between the predicted results from off-line simulation, and the actual results obtained from the HIL simulation indicate that a gap in the knowledge of the system exists. An investigation into this gap in the knowledge was undertaken, examining the effect of potentially relevant phenomena through off-line simulation response. This process of investigation represents low cost iterations in the IWC development process, made using the scale model system.

Analysis of the system indicated that the instability was attributable to a lag in the wheel speed feedback. This lag is inherent to the wheel speed signal processing hardware. Before investigation potential solutions to the problem, the relevance of the problem to the Hylander vehicle was established. The same wheel speed measurement hardware is employed on the physical scale model as per the Hylander vehicle. Thus, the same lag in the measurement signal will exist. Through theoretical analysis and off-line simulation of the full-scale vehicle, the author identified that a similar lag on the full-scale vehicle system would result in operation which was not representative of a conventional 4x4, and in some operational modes (gearing combinations), would be unstable.

As physical alterations of the scale model hardware are outside of the scope of this application, a software approach to the problem is devised. A predictor, adapted from the Smith predictor arrangement [66], predicts the wheel speed using a model of the signal lag and wheel inertia. The net torque acting on the wheel is estimated using the known applied torque, and an estimate of the resistive torque, generated as a function of the error between the estimated and measured wheel speeds [59].

Figure 12 illustrates the results of the HIL simulation using the predictor arrangement to overcome the effects of the wheel speed measurement lag. Results from ideal, scaled off-line simulation of the system are superimposed on the HIL simulation results. From the two results the IWC controller can be seen to meet the customer requirements (represented by the off-line simulation results).

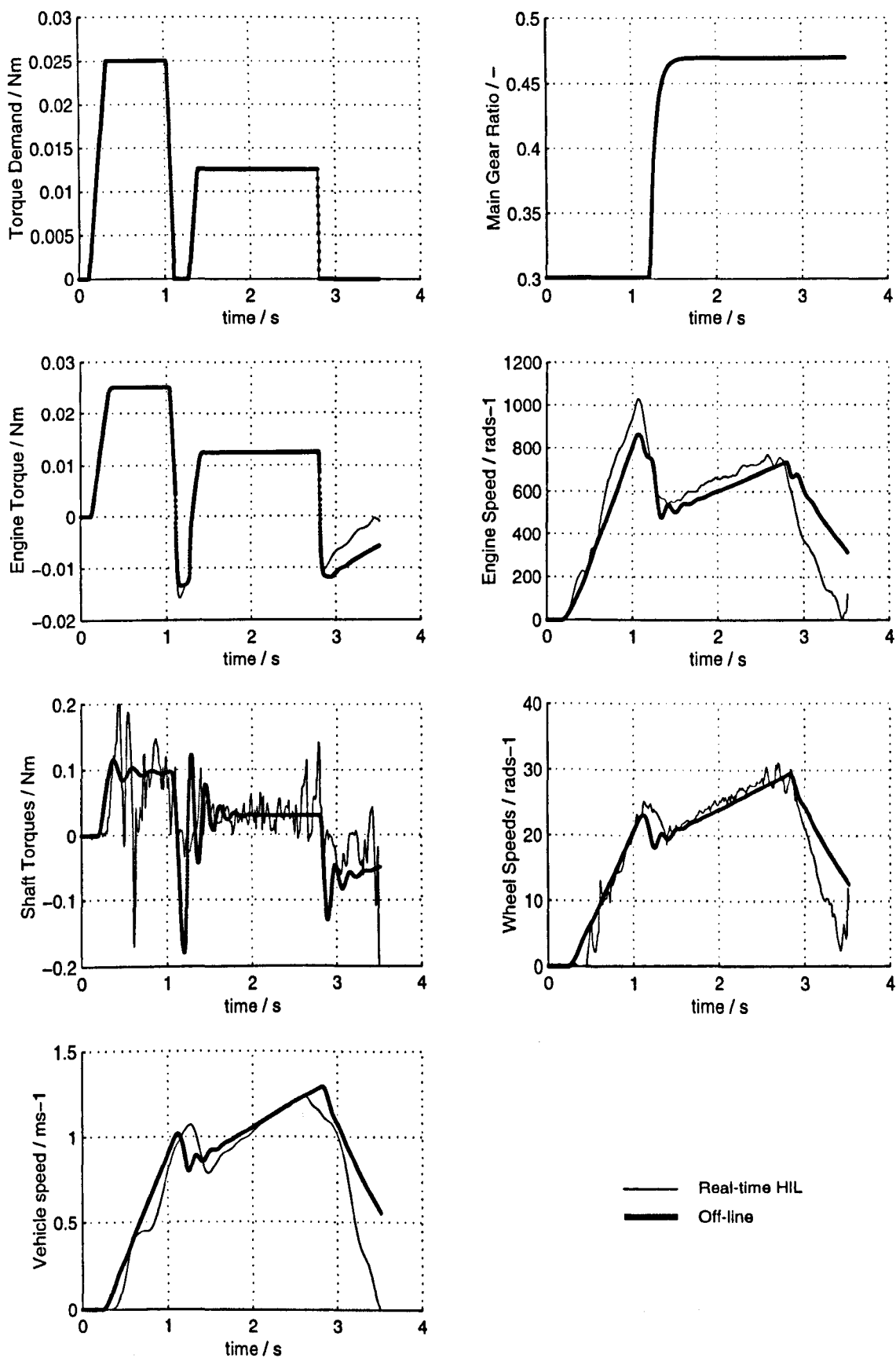


Figure 12. Improved HIL Simulation Results



Some variations between the two results can be seen at the end of the test run. This is due to other effects not modelled in the off-line simulations which would not be a factor on the Hylander vehicle, but exist on the physical scale model, e.g. trailing wires which supply power and signalling to the model. A notable point of operation is the ability of the system to reject noise disturbances acting on the wheel speed signals.

Other test results can be found in [59], verifying that the customer's requirements have been met. The operational behaviour of the vehicle has been demonstrated to the customer, and the customer has verified that this operation meets their initial requirement [67].

#### **4.7.2 Development of the Process**

The process of rapid prototyping an IWC strategy has been followed as described in [38]. The author has identified a distinct stage in the process relevant to the Hylander scale model, where the simulation models are scaled. The author has also identified that it is appropriate in the development of an off-line simulation to separate the elements of the system, which constitute the controller from the plant. This assists in the process of applying the controller in HIL simulation.

Through the application of the rapid prototyping process (RPP), the author has identified that the development of mathematical models representative of the plant (vehicle) can be time consuming. Hence the plant/vehicle model used in this application is relatively simple. In some IWC strategy applications, a direct implementation of a controller in HIL simulation may be more appropriate than an off-

line simulation stage. This will be particularly true where effects that are complex to model mathematically are expected to dominate the system response.

Scaling of operation highlighted that the scaling of time may present stability issues where the sample rate of the system is critical. In such instances, the rapid controller prototyping platform (dSPACE™) must be able to run an integration step size that is smaller than the Hylander vehicle implementation controller platform by the time scale factor.

#### **4.7.3 Further Development**

Having developed the IWC strategy at a conceptual level, the next logical step is to implement the strategy on the Hylander vehicle. The software predictor approach developed is suitable, but will require tuning if applied on the Hylander vehicle. However, the author recommends that a feasibility study into reduction of the signal lag through development of the instrumentation hardware should be the next course of action. This is in recognition of the fact that extra signal processing introduced in the software will increase the processing overhead of the system, limiting the sample rate of the controller. A more appropriate instrumentation approach may be the application of a digital pickup with digital signal processing, removing the requirement for smoothing capacitance used in the current analogue signal processing.

Prior to full implementation on the Hylander vehicle, the scale model system should be validated as representative of the Hylander vehicle and the implications of differences between the two systems understood in the context of IWC strategy operation.

## **4.8 Conclusions**

The limits of the Hylander scale model system have been tested in a complex, closed loop control application containing transient, oscillatory dynamics. Through this application a case study example of the IWC rapid prototyping process has been produced.

Through this case study, the IWC rapid prototyping process has been improved through modelling of the controller distinctly from the plant in off-line simulation. Also, in the identification of criteria for the application of an off-line simulation stage in the RPP.

The strategy developed by the author has been validated as operating the physical scale model in a manner representative of a conventional 4x4 vehicle (Defender 90). Areas of knowledge developed through the application of this strategy have been related to the Hylander vehicle, and appropriate suggestions for further investigation proposed.

The aims of the main research have been met in full. The technical appropriateness of the scale model system to the rapid prototyping and development of IWC strategies at a conceptual level in order to support the Hylander project has been validated.

## 5 Other Areas of Application

This section details applications for which the Hylander scale model has been used, outside of the main research. The aim of this section is to highlight other benefits of using the physical scale model not considered in the initial conception of the model. To illustrate the breadth of application, the author has generated a map of areas in which the scale model has been applied (see figure 13). The areas covered through the main research are highlighted as; development of IWC strategies, and the process of their development and application. Each of the other areas is discussed in the following sections.

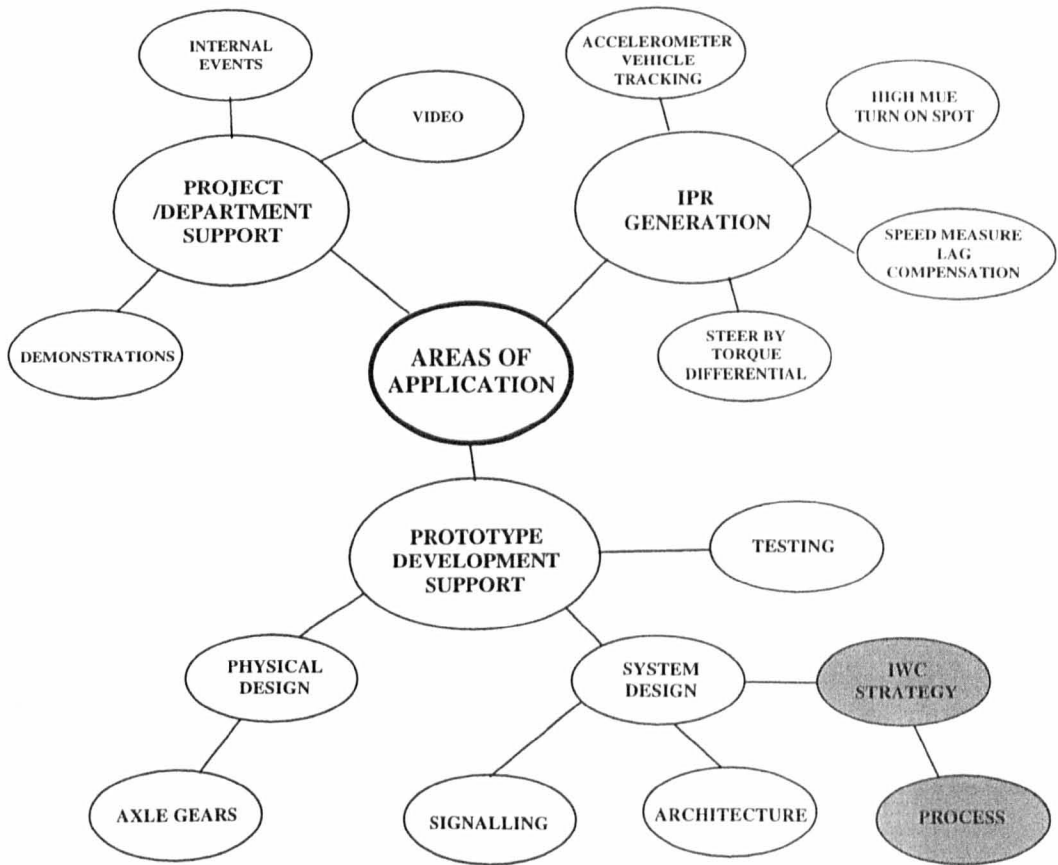


Figure 13. Mapping of Scale Model Applications

## 5.1 IPR Generation

In [38], the author discusses the role of the Hylander scale model system both as a tool for concept development, but also as a tool for concept generation. Developing concepts on the scale model directly, in a less formal manner than in development, ideas can be rapidly implemented. The results of such an approach have led to the application of a simple torque splitting algorithm to be used to demonstrate the potential capability of the Hylander vehicle to perform a 'tank turn' i.e. turn on the spot. Torque is split left/right by an amount according to a steering input.

Using this technique the model can be driven as a tank, with separate torque inputs for each side of the vehicle. Steering can be effected without turning the wheels, and conversely, the wheels can be turned without a direct steering input. This effect can be used to automate a multi-point turn, turning the wheels through a torque imbalance. Two patent applications have been generated from this work [68]:

- High mue turn on spot – on a high friction surface, the applied torque may not be sufficient to break traction. Various strategies to overcome this are described.
- Steer by torque differential – the ability to turn steerable wheels, linked by pivoted beam, is applied to the application of four wheel steering.

IPR has been generated in other areas using knowledge gained in the development and application of the Hylander scale model. Patent applications for signal processing and instrumentation techniques provide a prime example of this.

The author has also supported a patent application through the application of theory to support an invention based on the mimicking of expert driver behaviour [69]. This

patent application is filed in the UK, EU and US, and has passed the search stages, validating the patent to be a novel idea.

## **5.2 Prototype Development Support**

Through the construction of the scale model system, and its implementation in a feedback IWC control application, a number of lessons were generated which are applicable to the design and development of the full-scale prototype vehicle. These lessons are discussed in the following sections, including examples of application in the design, build and test of the full-scale vehicle where appropriate.

### **5.2.1 Testing**

Subsequent to the authors findings in [40], where the need to characterise the relationship between the wheel torque and motor torque signal is identified, the Hylander vehicle is to be tested using a dynamometer to evaluate variations between the individual wheel drives. By highlighting this requirement at an early stage in the development process, the development team is in a position to book such facilities well in advance. Due to the demand on such facilities within Rover Group, this is important in order to reduce the lead-time in vehicle development. Currently it is not known whether an appropriate dynamometer facility is available within Rover, or whether this facility will have to be out sourced [65].

In the characterisation work undertaken in [40], the author has characterised torque losses between the motor and the wheel as a function of the motor torque and the

motor/wheel speed. The author also identified oil temperature in the transmission as a potential variable in the characterisation of wheel torque. The Hylander development team has committed [67] to evaluate these effects when the drivetrain is characterised on a dynamometer.

### **5.2.2 Physical Design**

The issue of oil temperature as a factor in the calculation of wheel torque also raised a design issue. On the Hylander vehicle, the motor drives through a gearbox, along a drive shaft and then through half a differential (i.e. a simple gear ratio) mounted in the axle. To effect two drivelines per axle, two differential housings have been mounted back to back. It is in these differentials that the Hylander transmission expert expects the greatest effect of torque variation due to oil temperature [65].

In the initial design, the oil volumes of the two differentials on each axle were to be separated by a baffle. The author proposed that a common oil volume be employed, allowing the two differentials to heat at the same rate. If only one drive is utilised, it is predicted that the differential gear will effect mixing of the oil [65].

Through commonisation of characteristics across an axle, the likelihood of errors in output torque prediction causing the vehicle to yaw in an undesirable manner is reduced. Variations between the front and rear axles may cause some tyre scrubbing. Also, if temperature effects are deemed significant enough to warrant instrumentation, only two sensors as opposed to four are required. This will become a key factor as the vehicle develops due to bandwidth availability on the CAN bus and I/O limitations of the hardware.

### 5.2.3 System Design

In [40], the author recommends that all on board signals are transmitted in a digital form to reduce noise effects, and that analogue instrumentation signals are digitised at a point as close to the sensor as possible. The Hylander control systems architecture has been designed based on this advice. The backbone of this architecture is a digital CAN bus which talks to various on board systems. Instrumentation signals are processed locally and transmitted digitally to the IWC controller via the CAN bus.

The application of IWC on the scale model [59] highlighted that the sample rate of the system could have an effect on system stability. This has led to a study currently being undertaken into the minimum guaranteed sample rate available over the CAN bus for the Hylander vehicle system, and the minimum allowable sample rate in order to effect a complex control strategy (e.g. the conventional 4x4 strategy).

The Hylander scale model has been developed specifically to utilise the same or representative instrumentation where possible. Hence the scale model can be used to develop and test signal processing and instrumentation strategies for the vehicle. In the application of wheel speed measurement, the Hylander vehicle has adopted instrumentation used on the scale model.

In [40] the motor output shaft is instrumented using a non-contact sensor (Hall effect switch) to determine direction (digital output providing either forward or reverse). On the Hylander vehicle, the motor torque and direction are specified inputs to the motor controller. It was the opinion of the development team that the specified direction input would imply the direction of rotation of the wheel [67]. However, after further



investigation, the author illustrated that if the motor were to receive a positive, forward torque demand, the wheel could rotate in reverse if on a hill with a gradient such that the effect of gravity on the vehicle is sufficient to overcome the applied torque. It transpired that this effect had come to light in a previous research project [70] using the same motor drive technology.

The signal processing associated with wheel speed measurement on the model has also been transferred to the Hylander vehicle, and to other project vehicles (HE4 [70] / Hero [71]). The ABS magnetic pickup can see high-speed impulses at low speeds due to vibrations in the drivetrain. Signal processing developed by the author filter out these impulses using an inferencing algorithm based on a second speed measurement (taken from the direction sensor).

### **5.3 Project / Department Support**

The role of the scale model during the course of the work has been significant in promoting the work of the department. The scale model has been used at internal events as a static demonstration piece, for example, Technology Planning Event, June 1998 and Drivetrain Advanced Technology Event, August 1998. These events are held to raise the profile of research projects within the Rover Group.

More recently, the author produced a video of the scale model in operation, demonstrating the capabilities of an IWC vehicle through simple tank turn/turn on spot strategies (see section 5.1 of this report). This has been used both in Rover, and in

BMW to display innovation in the area of 4WD that has the potential to significantly alter current thinking of the bounds of vehicle performance in off-road applications.

One outcome of this promotional work has been the suggestion from BMW [72] that the Hylander vehicle may have a role to play in promoting the brand image of Land Rover through its use in a future 'James Bond' movie. BMW invests heavily in this format as a marketing tool.

## **5.4 Conclusions**

The author has highlighted a number of ways in which the physical scale model has been utilised to support the Hylander vehicle, the Hylander project, and potentially the Hybrid department and Land Rover.

## **6 Discussion**

Through the main research the author has demonstrated the application of a scale model system to the development of an IWC strategy. Areas where the physical scale model has supported the technical development of the Hylander vehicle have been highlighted in section 5.2 of this report.

On a broader level the scale model system has supported the Hylander project through improvements made to the process of IWC strategy development, and through promotion of the project within the business, raising awareness of the potential of the technology.

The company or business benefits through the generation of IPR, protecting the potential of the technology as early as possible. The generation of IPR is a result of knowledge gained through the project, which is considered to represent a potential benefit to the business, either currently or in the future. As discussed in section 2.5 of this report, the generation of this knowledge has an associated cost. The purpose of a part-prototyping approach was highlighted as attaining the knowledge at a reduced cost. The next section discusses the costs associated with the scale model system in relation to the Hylander vehicle. The following section provides a critical assessment of the suitability of the scale model approach to the development of IWC strategies for the Hylander vehicle. The final section builds upon this to develop a set of criteria for the selection of part prototyping as a development tool in other applications.

6.1 Cost Implications of the Scale Model Project

6.1.1 Financial Cost Estimates

Table 2 lists cost estimates for the Hylander scale model and Hylander vehicle projects, based on information from [73].

	HYLANDER VEHICLE	SCALE MODEL
	£	£
VEHICLE CAPITAL COST	325k	5k (+40k)
VEHICLE BUILD /DEVELOPMENT COST *	402k+	128k
OPERATIONAL COST RATE / PER DAY *	983 <sup>♦#</sup>	428

\* based on man-hours charged at Rover Group standard rate.

\* based on man hours + Rover vehicle testing cost rate

\*two people required to operate Hylander vehicle.

Table 2. Project Cost

The vehicle capital cost represents the purchase cost of the physical vehicle components. For the scale model system, two figures are quoted. £5k represents the budget for the project, and £40k the purchase cost of the dSPACE™ equipment. This cost may be offset against other projects in which it is utilised.

The vehicle build/development cost represents the cost incurred in building and developing the vehicle (labour and overheads). This costs are slightly misleading as they represent estimates of current spend. As indicated by the '+', the Hylander vehicle is still in its build phase and is yet to enter development. From figure 4, it can be seen that the cost associated with the Hylander vehicle is likely to increase dramatically

during the latter stages of the vehicle development programme. The scale model build is complete, and a high level of development has been undertaken.

The operational cost rate represents the cost of actually running the Hylander vehicle and scale model (labour, overheads, test facilities) on a per day basis. This cost rate does not take into account the additional costs associated with the potential risk to human health in the manual operation of the Hylander vehicle. The total operational cost is a function of the cost rate, and the time taken to implement an IWC strategy on the vehicle.

### **6.1.2 Financial Savings**

In the previous section, the costs associated with the Hylander scale model is estimated. These costs are a part of the Hylander project cost, but are additional to the costs quoted for the Hylander vehicle. The figures illustrate that the scale model is both cheaper to produce, and to operate than the Hylander vehicle, but do not indicate how the scale model could potentially reduce the overall project cost.

The model will not reduce the cost rate associated with development on the Hylander vehicle, but could reduce the overall development cost by:

- **Reducing the development time using rapid prototyping tools** - On the scale model, the system is not safety related, and auto generated code can be used to control the model. On the Hylander vehicle, industry guidelines suggest a more visible process of code generation that can be verified against requirements [74]. The MathWorks Real-Time Workshop product is specifically marketed as not being suitable for safety related applications [75]. This introduces the requirement

software engineering expertise in the development and implementation of IWC strategies on the Hylander vehicle.

- **Undertaking development work at a lower cost rate** - see operational costs.
- **Undertaking development work at a lower financial risk** - in terms of financial risk, the Hylander vehicle is 65 times more 'risky' than the scale model. This risk is based on the cost of repair should the vehicle be damaged in operation, and is approximated to a factor of the vehicle capital cost.
- **Assisting in the identification of 'real' customer requirements** - customer requirements can be rapidly translated into an operational IWC strategy, and in most cases demonstrated using the scale model at a relatively low development cost. Specific areas where driver feedback is a key to a customer requirement may need a more direct application on the Hylander vehicle.
- **Filtering out 'dead-end' lines of research, thus optimising utilisation of the Hylander vehicle** - customer's expressed requirements may not translate to a workable solution, or may change. Development at a lower cost rate reduces the risk associated with these occurrences.

## **6.2 Technical Limitations of the Scale Model Project**

The role of the scale model system has been highlighted through this work as limited to the development of conceptual IWC strategies i.e. development of IWC in a generic manner rather than specific to the Hylander vehicle. This is due to the requirement for

validation of the model behaviour against that of the full-scale Hylander vehicle in order to prove its suitability in prototyping IWC for the full-scale vehicle.

The suitability of the scale model is uncertain due to modelling relaxations made in order to facilitate the build of the model within the practical constraints of the project. Most notable of these is the simplifications made in the model tyres. Full-scale vehicle tyres exhibit complex, non-linear relationships with the terrain which are difficult to reproduce through scale modelling. This is due to the requirement for an accurate scale tyre to reproduce physical build characteristics such as rubber material, tread pattern, and internal construction including a steel radial belt [2] in modern tyres. Without the support of a tyre manufacturer, the development of such a scale tyre would be further complicated by the tyre industries desire to keep variables such as the tyre compound secret for commercially competitive reasons. Previous work on the production of a scaled vehicle tyre has been undertaken [17], but this only attempts to reproduce one of the many characteristics of a full-scale tyre.

As the tyre/terrain characteristics are fundamental to the refinement of any IWC strategy, an accurate mathematical model incorporating dominant characteristics of both the tyre, terrain and their relationship will be required in order to support the development of IWC for the Hylander vehicle. This understanding may come from literature (generic modelling), a tyre manufacturer (tyre specific modelling), or experimental testing. As this area is the essence of the complexity in pure analytical modelling of off-road vehicle behaviour, the appropriateness of the scale model system in meeting the initial aim of developing IWC strategies to support the Hylander vehicle can be seen to be questionable.

In retrospect, given the complexity of the tyre/terrain interaction, a more accurate approach would be to use a HIL simulation approach with the vehicle dynamics mathematically modelled, and the tyre/terrain relationship represented by full-scale tyres in a test bed arrangement. This would also simplify the development of representative terrains as real world terrain materials could be utilised. Using such an approach, further understanding of the physics underpinning the tyre/terrain interface could be developed. This understanding is crucial to the development of IWC strategies to provide 'optimal' vehicle performance.

This does not detract from the value of the modelling approach in the other areas highlighted through this work. However, it does reduce the effectiveness and appropriateness of the initial aim of supporting the development of IWC strategies for the Hylander vehicle.

### **6.3 Global Implications**

The author has discussed the role of the scale model system in the context of the technical, project and business need. A more global or generic set of 'need' criteria for a part-prototype were presented in section 2.6 of this report, against which the requirement for a part-prototype was justified in the context of the Hylander project.

Through the application of the part-prototype or scale model system, the author has identified that the role of a physical prototype can be broader than meeting a technical need. This potential breadth of application has implications on the criteria where a part-prototype approach is appropriate, and hence in the requirements of that part-prototype.



aesthetic appearance of the model is not a relevant criterion for consideration. However, in the context of the broader role in which the model has actually been used, both the aesthetic appearance and other factors such as operational noise are all important in generating a favourable impression of the Hylander vehicle and its operation.

Other than technical development of IWC, promotion and demonstration have been the primary area of use of the scale model system. Hence a part-prototype can play a significant role in the justification of a project. In effect, the part-prototype may even act as a gateway in the development process, used to justify a full-scale prototype, as well as supporting its development. In such a role, the potential cost savings associated with the part-prototype may be huge given that a project may be identified at an early stage to be either technically infeasible, or outside of the requirements of the customer.

Using the part-prototype, as an early form of market research tool can be beneficial both in the filtering of appropriate ideas or approaches, but also in the generation of ideas as customers become aware of the potential of new technologies. Bringing the customer into the development process at an early stage ensures that 'blind alleys' are not pursued.

In section 1.1.1.2 of this report the author also identified that competitors developing similar technology to the Hylander vehicle had introduced the requirement for a tool which could be used to rapidly develop IWC ideas. This ties in with the generation of IPR to protect the company's interests in the future i.e. to protect the company's position in the market. This is another aspect where the use of a part-prototype may be appropriate.

Hence the author has identified six criteria for consideration in the selection of a part-prototyping approach:

- When a full prototype is expensive to construct.
- When a full prototype is expensive to operate.
- When a full prototype is safety related in its operation.
- When a full prototype exists in a new area of knowledge.
- Where the knowledge supported by the full prototype must be 'sold' to a customer.
- Where time pressures exist on the development of knowledge.

In line with the limitations of the scale model system highlighted in the previous section, the author has also identified that the use of scaling can potentially reduce the cost to build and operate a part prototype. However, the use of scale modelling must be considered in line with the complexity of scaling elements of the system which exhibit non-linear characteristics, and the expertise available to the researcher in order to undertake this form of modelling.

## **7 Conclusions**

The aims of the project have been met in part. A tool has been developed for the rapid prototyping of IWC concepts. This tool uses HIL simulation techniques, integrated with an 8<sup>th</sup> scale physical model of the Hylander IWC system. The tool has been demonstrated in the development of a complex, closed-loop IWC strategy, operating in manner representative of a conventional vehicle. However, due to the complexity of creating a representative scale tyre, this model is unsuited to the detailed refinement of IWC strategies for the Hylander vehicle.

The application has supported the Hylander project through identification of a requirement for an improved measurement of wheel speed in order to effect a stable system response. The application of digital rather than analogue sensors with digital signal processing has been recommended. To support the current instrumentation approach, a mathematical estimator has been applied on the scale model system.

Through the development and use of the tool, lessons learnt have been translated to the build of the Hylander vehicle in a number of areas. The tool has also been applied to promoting the potential of the technology within Rover and BMW.

The tool has generated IPR (patent applications), both through its development and application, supporting the future development of Land Rover products. These patents illustrate the potential of IWC to improve vehicle dynamic behaviour for off-road applications.

## 8 Future Work

Future work can be undertaken at a number of levels, reflecting the broad nature of this work.

### 8.1 Scale Model System

Development of the physical scale model itself could be undertaken in a number of areas. Primarily this development would focus on the generation of an accurate physical scale model of the tyres. To be viable this would require the support of a tyre manufacturer. As the role of the scale model is currently more appropriate as a planning and presentation tool, aesthetic development maybe an appropriate step e.g. creation of a body to make the vehicle look like a Land Rover Defender.

### 8.2 Hylander Project

The main research has focused on a specific IWC strategy. However, a range of potential IWC strategies exists [38]. Future work will include the development of IWC strategies to improve the dynamic behaviour of the vehicle in both a generic manner, and for specific operational conditions, for example a 'get me unstuck' mode. As knowledge is gained through this development, further refinements to the process of developing IWC strategies are envisaged by the author, supporting the Hylander project. Further research into an appropriate tool for the development IWC strategies is also required, considering both current analytical and potential HIL approaches as discussed in section 6.2.

### 8.3 Business

The portfolio includes IPR generated or applied for through the application of the scale model system in the development of IWC strategies. Future research into the potential of IWC will generate further IPR, protecting the position of the Land Rover business in a potential future market for IWC vehicles.

Currently, the approach of using a scale model system is under consideration for application in the area of advanced chassis control. A similar concept to the Hylander scale model system has been proposed with both IWC and active suspension for off-road vehicle development [77]. Such an approach should be re-evaluated in light of the author's findings regarding the complexity of tyre modelling.

### 8.4 Global

This work has focused on a specific application of the part-prototyping technique. However, its application is potentially much broader. As the author has identified, the progress of technology, and knowledge has led to the introduction of simulation software capable of replacing the use of modelling techniques. However, analytical simulation is commonly applied in the development of prototypes, in a variety of industries. The prototypes are constructed to confirm that the knowledge used to generate the analytical simulation has been applied correctly, and to identify areas for further investigation. In any such application, the six criteria for part-prototype selection are applicable in determining if a part-prototype is required, and in the generation of a requirement specification for that part-prototype.

Examples include:

- Any prototype for which the capital cost of the physical prototype represents a high financial risk if damaged, or if it fails to deliver the predicted results e.g. where the prototype is constructed from expensive materials.
- Any prototype where the energy, or manpower costs of operation are high e.g. a manual production line.
- Any prototype which requires a human operator, and which possess sufficient energy, or hazardous material to harm the operator or environment e.g. vehicles, heavy machinery, processes involving toxic chemicals, or nuclear power.
- Any prototype which explores a new area of knowledge e.g. the lunar rover [42].
- Any prototype where the concept must be sold to the customer, either internal or external to the business, e.g. the hovercraft concept [76].
- Any prototype where time to market is a predominant factor, e.g. consumer electronics.

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